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## SPATIOTEMPORAL CHARACTERISTICS OF VISUAL LOCALIZATION— PHASE II

Final Report  
Covering the Period September 1985 to September 1988

October 1988

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19. Abstract

large separations at large eccentricities, a qualitatively different mechanism appears to come into play. (A-1)



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## I RESEARCH OVERVIEW

The overall long-term goal of this research is to discover the nature of the human visual process that encodes information about the spatial extent of objects and their separations. For brevity, we will refer to this process as the "length gauge," indicating its essentially one-dimensional nature and capturing the fact that it estimates the properties of objects and their separations, rather than simply recording retinal distances.

The primary problem we confront is that this process it is not a simple function of retinal luminance distribution. Instead, it operates on the responses of other complex spatiotemporal processes. Thus, the results obtained in an experiment may depend primarily on the properties of the prior spatiotemporal processes, primarily on the properties of the length gauge, or on some combination of the two sets of properties. The difficulty is to determine which effects should be attributed to the length gauge itself, and which should be attributed to other stages of visual processing. Our working assumption is that one should account for as much of the data as possible at the earlier stages of processing, about which more is known, and attribute properties to the length gauge only when necessary. This is simply the normal conservative approach to postulating the existence of a new mechanism.

We use a local spatial-filters model of early spatial vision, such as that proposed by Wilson and Bergen (1979), as our model of the initial stages of spatial visual processing. This model has three main features: (1) at each retinal location there are numerous spatial filters tuned to different spatial frequency ranges; (2) the temporal properties of the high- and low-spatial-frequency filters differ, with the high-spatial-frequency filters integrating information over a longer time than the low; and (3) the highest spatial-frequency range detected decreases with increasing retinal eccentricity. To date, our conclusions have not depended on more specific details of the model. Using these assumptions, we accounted for some fundamental properties of separation discrimination thresholds at the local spatial-filters stage and have had to attribute other properties to the length gauge itself.

Much of the research performed under this contract focused on one central question: Can separation discrimination thresholds be accounted for strictly in terms of the local spatial filters, or is another stage of processing required? Finding that another stage is

definitely required changed the research focus to answering the question: What are the properties of this subsequent stage, this "length gauge"?

## **II LOCAL SPATIAL FILTERS AND THE LENGTH GAUGE: BASIC STUDIES**

### **A. Exposure Duration Effects in Separation Discrimination Thresholds**

We examined the effect of exposure duration on separation discrimination thresholds at a number of average separations. We found that increasing exposure duration (from 100 to 400 milliseconds (ms)) decreased threshold at small separations, as had previously been reported in the literature (Baron and Westheimer, 1973; Foley and Tyler, 1976; Hadani, Meiri, and Guri, 1984), but had a negligible effect at large separations (separations greater than about 15-20 arcmin). However, if we changed the stimulus from a pair of luminance bars to a pair of high-spatial-frequency (HSF) targets (strips of Gaussian-modulated, high-spatial-frequency gratings), then exposure duration had a substantial effect even when the separation was large. We concluded that the exposure duration effect occurs whenever HSF filters are conveying the relevant information. In the case of small separations, HSF filters are the only ones that can detect the targets individually, and in the case of HSF targets separated by large distances, they are the only filters that can detect the targets at all. This type of spatiotemporal interaction in the local spatial filters can help reveal roughly which range of spatial-frequency filters are being used in a given experimental situation. If there is an exposure duration effect, then it is possible that HSF filters are involved. If there is no such effect, then low-spatial-frequency (LSF) filters are implicated.

The exposure duration results were reported in the *Journal of the Optical Society of America A* (Burbeck, 1986).

### **B. Position and Spatial Frequency in Large-Scale Localization**

In these studies, we looked at the effect of changing the spatial characteristics of the individual targets on separation discrimination thresholds. We found remarkably little effect. Separation discrimination thresholds are the same for LSF targets, HSF targets, and for a stimulus consisting of one of each. Thresholds are also unaffected by changing the contrast polarity of one target -- so that one is white and one black -- or by enhancing the HSF content of a broadband stimulus. Collectively, the results indicate that the spatial

filters themselves are incapable of accounting for large-scale separation discrimination thresholds. They further indicate that the mechanism that is responsible for these thresholds, which we call the *length gauge*, is equally linked to all spatial filters and can operate across types of spatial-frequency filters as well as it can operate within one type. We conclude that the slope of the Weber function for separation discrimination thresholds,  $\Delta s$  plotted as a function of  $s$ , cannot be accounted for by the properties of the local spatial filters, but must be attributed to the length gauge itself.

These results are reported in two papers in *Vision Research* (Burbeck, 1987a; 1988).

### C. Role of Retinal Inhomogeneity in Separation Discrimination Judgments

Before finally eliminating local spatial filters as the primary determinants of the slope of the Weber function for separation discrimination, we examined the effects of retinal inhomogeneity on separation discrimination thresholds. In the standard experimental paradigm, the retinal eccentricity of the individual targets increases as the separation between them increases. Thus, the decrease in accuracy could have arisen from the decrease in spatial resolution with increasing eccentricity. To test this possibility, we measured separation discrimination for targets presented on isoeccentric arcs.

A manuscript is in preparation on this topic (a draft is included as Appendix A). Dr. Yap will be presenting the material at the Optical Society of America Annual Meeting in October 1988.

### D. Orientation

The other basic spatial dimension to be considered is orientation. There are two key questions here: Does the length gauge selectively use spatial filters of a given orientation, e.g. those perpendicular to the direction of measurement? and Does the length gauge itself have preferred directions of measurement?

We have addressed the second question in an experiment using small square targets in which the direction of measurement was systematically manipulated. We found no oblique effect for any of the three observers tested. Data for two of the observers are shown in Figure 1. Data for the third observer are similar. We did find a preference for vertical over horizontal for two of the three observers. However, the data do not

collectively indicate the type of effect that one would expect if the length gauge had an intrinsic preference for specific orientations.

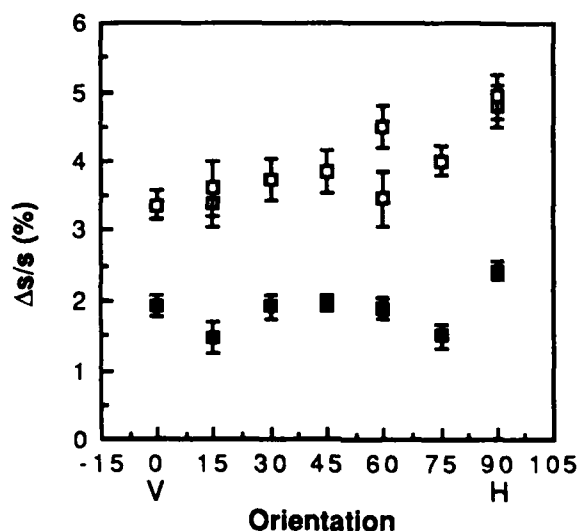


Figure 1 Separation Discrimination Thresholds Measured as a Function of the Orientation of the Measurement Axis. The targets were small squares. Data are shown for two observers.

Research on the problem of whether there is a preferred spatial filter orientation is not yet complete. We have investigated the problem using line stimuli and found no effect of target orientation, but we have been limited in our pursuit of this question by our hardware, which cannot be addressed pixel by pixel and, therefore, cannot give us Gabor patches of various orientations, which would be the ideal stimuli. Dr. Lex Toet, of the Institute for Sensory Physiology in The Netherlands, may be collaborating with us on answering this question. He is interested in our approach and has the necessary facilities for conducting these experiments.

### III THE LENGTH GAUGE

#### A. Size Constancy

Using a frequency discrimination paradigm, we examined the relationship of depth information and size judgments. We compared frequency discrimination thresholds for a pair of gratings seen at a common viewing distance with thresholds for a pair seen at different viewing distances. Thresholds were only very slightly elevated by changing the viewing distance to one of the gratings, even though the retinal spatial frequency (cycles/degree of visual angle) was changed by a factor of two in the process. Collectively, the data showed quite convincingly that observers are unable to compare retinal distances, but can only estimate the properties of the actual object. They cannot ignore information about the depth of the objects.

These results were reported in the *Journal of the Optical Society of America A* (Burbeck, 1987b).

#### B. Separation Discrimination in the Presence of Flanking Lines

One of the key facts remaining to be uncovered is the relationship between the local spatial filters and the length gauge itself. In this study we ask the question: Can the length gauge selectively use the spatial filter that carries the best information, or is the response of the length gauge unalterably affected by the responses of all filters that detect the targets? We present several lines of evidence indicating that when the targets are crowded by the presence of flanking lines then high-spatial-frequency filters are used, whereas when they are not so crowded, lower-spatial-frequency filters appear to be used.

These experiments are reported in a draft manuscript, "The Role of Local Spatial Filters in Length Judgments," which is included as Appendix B.

These experiments have also suggested a means of capturing the phenomenon of grouping in a quantitative, objective manner. When the flanking lines are sufficiently near the targets, then the observer makes his response quickly (increasing exposure duration from 100 to 500 ms has little effect), suggesting the use of LSF filters, and he makes his judgment on the basis of the average position of the target and the near flanking lines.

When the flanking lines are farther away from the targets, then he makes his decision more slowly (increasing exposure duration has a large effect), suggesting the use of HSF filters, and he makes his judgment on the basis of the positions of the individual target lines. Thus, it appears that exposure duration effects can provide a means of telling when the objects group and when they do not: When they group, exposure duration has only a minimal effect at most; when they do not group, exposure duration has a large effect. We are continuing to explore this phenomenon. For example, we are conducting experiments to determine the relationship between the spatial range over which grouping occurs and the separation between the targets. We find this research development particularly exciting because it appears to offer a firm quantitative handle on a basic perceptual phenomenon.

### **C. Form vs. Separation**

This research began as a component of a line of investigation, discussed below, that was designed to uncover which stimulus dimensions are treated independently by the length gauge, which inhibit each other, and which enhance each other. In this experiment, we examined the effects of having the dimension orthogonal to the measurement axis providing useful information simultaneously. Specifically, if the two lines that create the separation discrimination stimulus are the same length as the average separation, is performance enhanced? The answer is no, as shown in Figure 2. Providing a reference length in the orthogonal direction does not improve the observer's performance.

However, if the stimulus is changed from a pair of lines to a single rectangle whose height is changed but whose width is held constant, then when the width equals the average (perceived) height, performance improves markedly for the long exposure (500 ms) as shown in Figure 3, although it is unaffected at the short exposure (100 ms). This exposure duration effect suggests once again that HSF filters are being employed. But why are they used only when the judgment concerns squareness and not when the observer is discriminating one rectangle from another? One possibility is that these stimuli tap basically different visual pathways, of the type recently described by Livingstone and Hubel (1988). It may be that the distance between two lines, or the height of a rectangle, is evaluated using the length gauge, which we know does not integrate information over a long period of time, and that discrimination of a tall rectangle from a short one -- with squareness serving as the demarcation between the two -- is a form judgment. The "form mechanism" being described in the literature has long temporal integration times and higher

spatial resolution, being associated with the parvocellular layers of the lateral geniculate nucleus (LGN). The other major pathway, associated with the magnocellular layers of the LGN, is thought to be responsible for motion and depth perception. Perhaps length perception should be included with motion and depth because of the short integration times and poor spatial resolution.

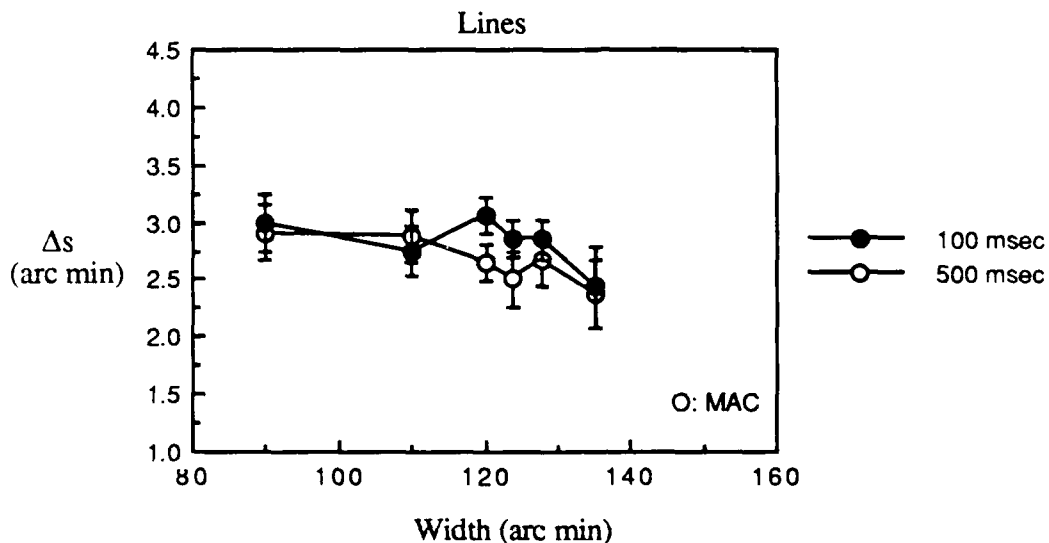


Figure 2 Separation Discrimination Thresholds for a Pair of Lines with an Average Separation of 120 Arcmin, Measured as a Function of the Length of the Target Lines. Data are shown for two exposure durations.

The connections to the physiology are, at present, merely suggestive, but the psychophysical phenomenon is intriguing and quite real. We are investigating it in more detail and so far have found the following. A diamond shape does not have the same property as the square. As shown in Figure 4, performance is constant across the point at which the diamond is symmetrical. Similarly, if the rectangular stimulus is moved to 5° retinal eccentricity, the effect disappears, as shown in Figure 5.

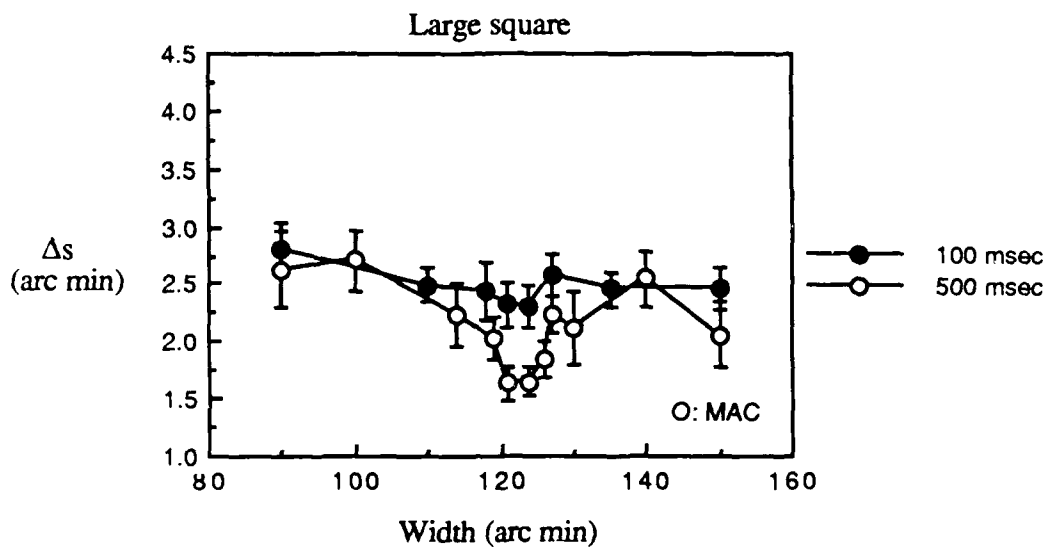


Figure 3 Separation Discrimination Thresholds for a Rectangle Whose Height Varied from Trial to Trial and Averaged 120 Arcmin. The width of the rectangle was a parameter of the experiment. Data are shown for two exposure durations.

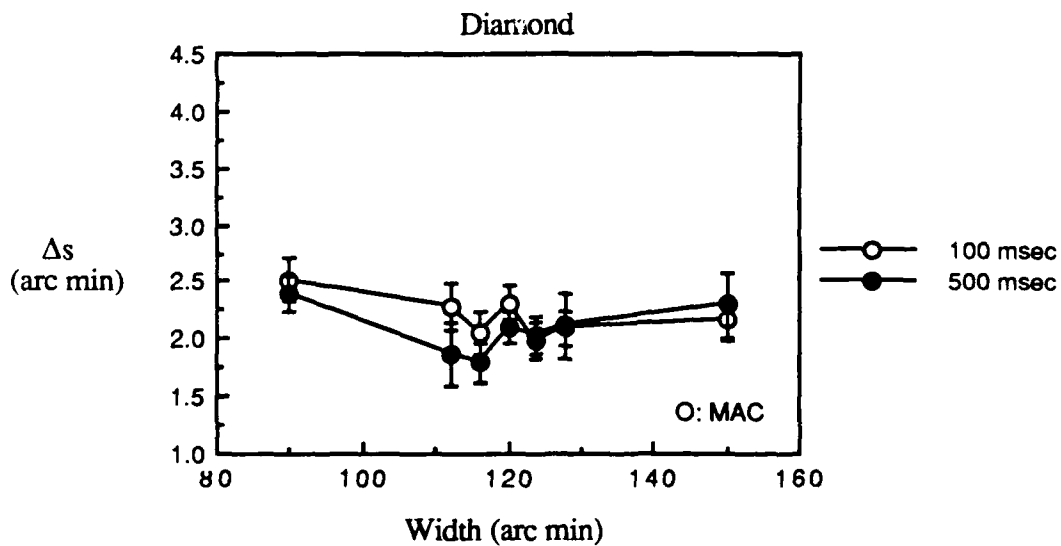


Figure 4 Same as Figure 3 Except that the Stimulus Was Rotated by 45° Using a Dove Prism.

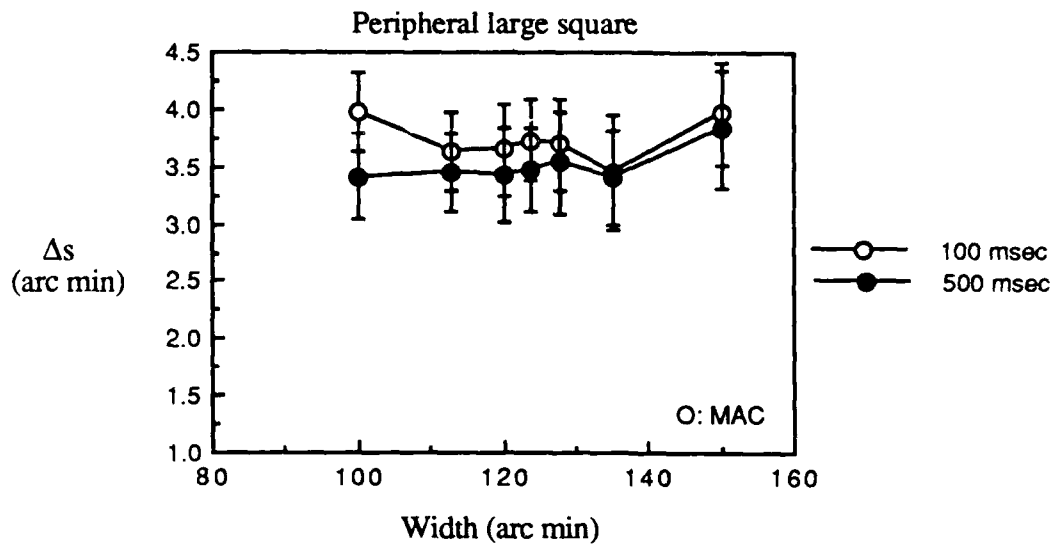


Figure 5 Same as Figure 3 Except that the Rectangular Stimulus Was Presented at 5° Retinal Eccentricity

A foveal rectangle of much smaller extent (0.21° rather than the 2° used above) was also tried. The data are shown in Figure 6. Exposure duration had an effect at all rectangle widths measured, consistent with previous findings. Perhaps the form mechanism is triggered whenever the object is small enough or special enough. We are continuing to work to discover just what "special" means in this case. Our next steps will be to measure thresholds with a larger rectangle in the periphery and to measure thresholds for the foveal stimulus with a diffusion screen to test our hypothesis that higher-spatial-frequency filters are being used when the target is nearly square. This research could have two important outcomes: it could demonstrate that form and length are mediated by separate visual processes; and, it could reveal a class of forms that the human visual system demonstrably treats as special.

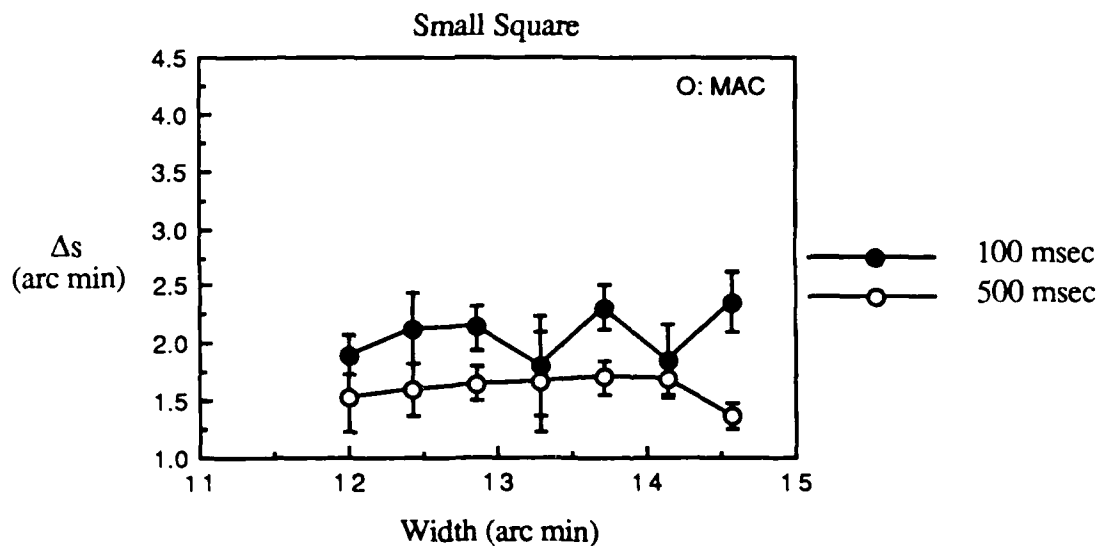


Figure 6 Same as Figure 3, Except that the Average Height of the Rectangle Was 12.8 Arcmin.

#### D. Serial vs. Parallel Processing of Length Information

A visual pattern may be discriminated either in parallel or in series from a background of other textural elements (Bergen and Julesz, 1983; Treisman, 1977;1982). In this experiment we examined whether the length gauge is able to process two separations simultaneously (i.e., in parallel) or whether the comparison process is serial. To do so we compared performance of two tasks: bisection, in which the reference and test separations are present simultaneously, and separation discrimination, in which the reference and test are presented sequentially, with a 1500-ms interstimulus interval (ISI). If the length gauge processes distance information serially, bisection thresholds should be higher than separation discrimination thresholds for short durations. However, if the length gauge is able to process more than one distance at a time, then the bisection threshold should be at least as low as the separation discrimination threshold for all target durations.

In each task, the observer's job was to decide whether the distance between the top target and the middle target was larger or smaller than the distance between the bottom target and the middle target. In the bisection task, both separations were presented simultaneously. In the separation discrimination task, the top and middle pair of targets were presented in the first temporal interval and the bottom and middle pair of targets were

presented in the second interval. To ensure accurate fixation in both tasks, onset of the middle target preceded presentation of the top and bottom targets by 500 ms. To prevent processing from continuing after the targets were extinguished, a mask was presented immediately after each stimulus presentation. The masks were high-contrast grating patches and were presented for 500 ms.

We chose two target separations:  $2.8^\circ$ , which exhibits no exposure-duration effect in going from 100 to 500 ms, and is presumably mediated by LSF filters, and 11 arc min, which does exhibit an exposure duration effect when the exposure goes from 100 to 500 ms, and is presumably mediated by HSF filters. The results are shown in Figure 7. For both target separations, bisection thresholds were higher than separation discrimination thresholds for short durations but were lower for longer durations. The crossover occurred at approximately 180 ms. These surprising results suggest that the length gauge processes distance information serially. The results also support the idea that the length gauge operates even at small separations, where most models are based on the responses of single filters (Klein and Levi, 1985; Wilson, 1986). We plan to report these results in a research note to *Vision Research*.

#### **E. Methodology of Separation Discrimination**

A standard paradigm for separation discrimination experiments is to present a single stimulus on each trial and have the observer report whether the stimulus separation is larger or smaller than the average separation that he has seen on previous trials. This paradigm provides no explicit referent for the observer. Dr. Dan Swift, of the University of Michigan, Dearborn, and I examined this problem by comparing thresholds obtained with the single-interval technique to thresholds obtained with a standard two-interval, forced-choice technique, in which the referent was presented on every trial. We found, quite surprisingly, that thresholds were at most 20% higher for the single-interval technique than for the two-interval technique. Observers were able to extract and

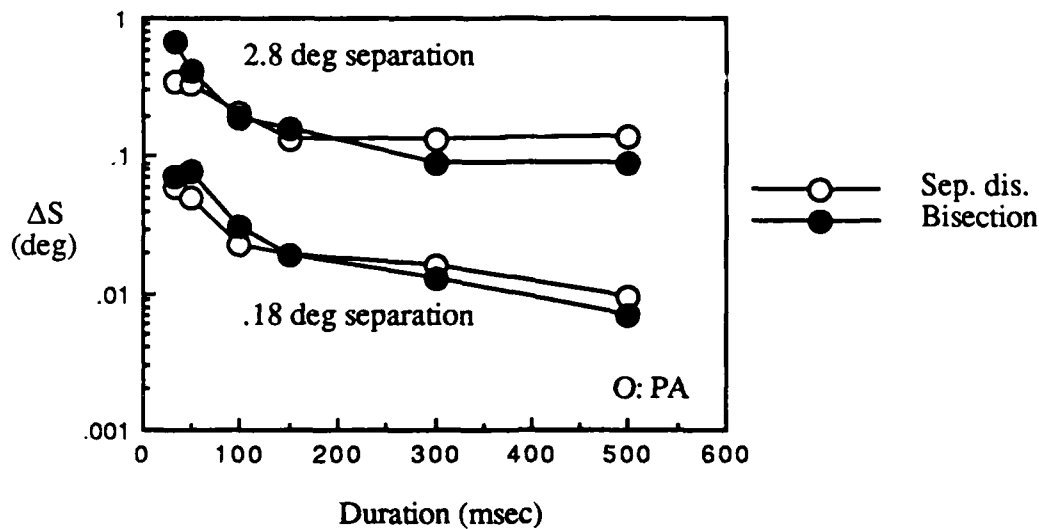


Figure 7 Separation Discrimination (Sep. dis.) and Bisection Thresholds Measured as a Function of Exposure Duration with a High-Contrast Mask Following Each Stimulus Presentation. Data are shown for two separations.

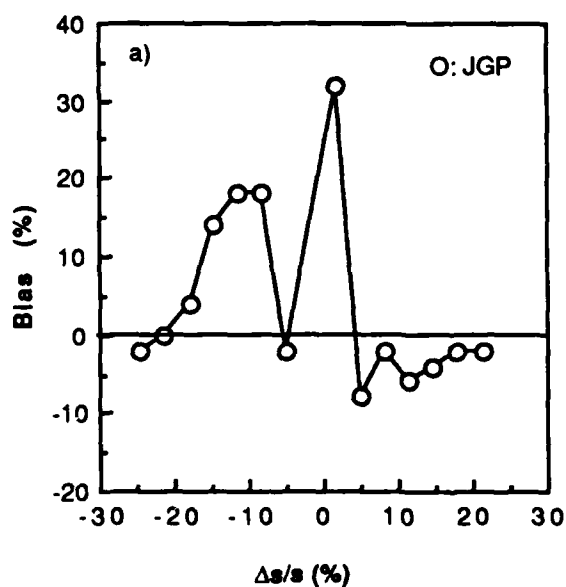
remember an average separation almost as accurately as they could encode and remember information about a referent presented immediately before each test stimulus. The residual difference disappeared if the range of test stimuli in the single-interval paradigm was restricted to just two values.

This finding cannot be accounted for by any simple model of the observer's performance. We modeled the observer's calculation of the average by taking a weighted average of the  $N$  previous trials, using an exponential decay for the weighting function. No values of the decay constant or of the window size,  $N$ , yielded a variance that was small enough to be consistent with the observer's performance. Apparently the observer has a more efficient algorithm for averaging the separations he has seen. This type of mechanism would act like a calibration system. We have also done other two-interval experiments that shed light on this problem. They are continuing to be developed.

Some of these results will be reported at the Optical Society of America annual meeting in October 1988.

## F. Dependence of Perceived Separation on Target Size

We examined the effect of the target size on the perceived separation between the targets. Several of our studies point to the idea that size is encoded as a relative, not an absolute, value. In this study, we looked at the effect of the size of the target itself on the perceived separation. We measured the bias in separation discrimination thresholds using a two-interval paradigm in which the targets in the two intervals had different sizes. The targets were squares with sides of either 8 or 66 arcmin. The two targets in a single stimulus were always the same size. The observer's task was to compare the distance between the inner edges of two small squares with the distance between the inner edges of two large squares. Both orders of presentation, large then small and small then large, were used. No feedback was given. These results were compared to results obtained with all large squares. We found a significant bias in the observer's responses. The smaller squares looked farther apart than did the larger squares, as shown in Figure 8. Had the observer been comparing the centers of mass or the outer edges, the reverse effect would have held.



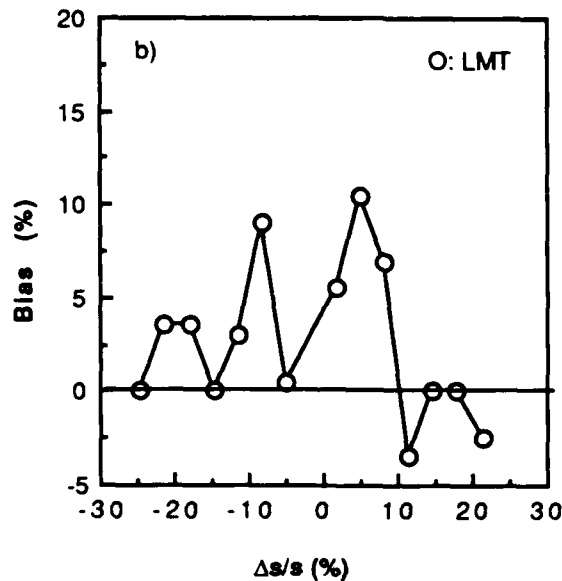


Figure 8 The Bias in Perceived Separation that Results when an Observer Compares the (inner-edge) Distance Between Two Small (8 arcmin) Squares with that Between Two Large (66 arcmin) Squares. The bias is obtained by subtracting the psychometric function obtained with squares of different sizes to that obtained when comparison is between squares of the same size. The positive bias at negative values of  $\Delta s/s$  indicates that the smaller squares looked farther apart than the larger ones.

The effect was a robust one. Changing from monocular to binocular viewing diminished the effect slightly but did not eliminate it. The finding points to a potent calibration process in which sizes are encoded relative to one another. We intend to report these results in a brief research note to *Vision Research*.

### G. Uncovering the Orthogonal Dimensions

At present this is simply a research idea. Our first experimental investigations of it led to the research on squares, reported in Section III-C. The idea is to uncover the way in which the length gauge uses stimulus information by manipulating two stimulus parameters simultaneously. There are two modes for this manipulation. The two stimulus dimensions can convey the same information simultaneously or the information in one dimension can be random with respect to that in the other. Results obtained in both cases

will be compared. For example, target length can be varied simultaneously with target separation. If the length gauge encodes information about the x and y dimension independently, then performance should be improved by  $\sqrt{2}$  when the two dimensions convey the same information, and performance should be unaffected when one dimension is varied randomly. This paradigm, which is a generalization of techniques that have been used in contrast detection studies, has intriguing possibilities for research on other types of discrimination as well.

## **IV RELATED AND UNRELATED TANGENTS**

### **A. Orthogonal Pattern Adaptation**

In an extension of previous research with Dr. Donald Kelly, we measured the effect of pattern adaptation when the test and adapting stimulus have the same spatial and temporal properties but orthogonal orientations. We found significant threshold elevations only at low spatial and high temporal frequencies, consistent with a previous masking study that we performed.

These results were reported in *Vision Research* (Kelly and Burbeck, 1987).

### **B. Rapid Pattern Discriminations**

This was a collaborative study with Dr. Ben Kröse, who was a postdoctoral fellow with Dr. Bela Julesz at California Institute of Technology at the time of the study. We investigated the effect on rapid pattern discriminations of distracters in the visual field. Our study was unique because we used the eyetracker to stabilize the retinal image. Stabilization enabled us to present the target in the periphery at a fixed location without the observer having to fixate. He could devote his full attention to the peripheral location at which the target would appear. Despite this freedom, we found significant effects on reaction time of the presence of distracters, even when they were 2° or 3° from the target.

This research is reported in the manuscript, "Lateral Interactions in Rapid Pattern Discrimination," which is included as Appendix C. It has just been submitted to *Spatial Vision*.

### **C. Pattern Adaptation Effects: Finding the Site of Length Judgments**

As noted above, it is often difficult to uncover the properties of the length gauge because of the substantial spatial processing that precedes it. Seeking a means to probe the properties of this process, we investigated the effects of pattern adaptation on frequency discrimination that had been reported in the literature (Regan and Beverley, 1983). Details of their experimental paradigm suggested that they might have found maximum effects

when the adapting grating and the test gratings had similar perceived spatial frequencies. Given the importance of perceived size in length judgments, this possibility seemed to be worth pursuing. However, we were unable to replicate Regan and Beverley's original findings.

This, and some related studies, are reported in a manuscript which is being revised for the *Journal of the Optical Society of America*, Series A, and which is included as Appendix D.

## COLLABORATIONS AND SCIENTIFIC VISITS

James Bergen (David Sarnoff Research Center, Princeton, N.J.) collaborated with me here during the month of September 1985, under AFOSR sponsorship. We explored the usefulness of the paradigm that he had used extensively (in another context) for investigating the localization mechanism. Dr. Bergen and I also had very fruitful discussions of the theoretical implications of my experimental work.

Alex Pentland (Computer Scientist, Artificial Intelligence Center, SRI) and I had an informal collaboration on the relationship between localizability and partitioning complex scenes for several months in 1986.

Martin A. Fischler (Program Director, Artificial Intelligence Center, SRI) and I met many times in 1986 to discuss the general problem of modeling human vision. This association was particularly valuable because we spent most of our time thinking about how to approach the most difficult problems in vision. The partitioning problem (that is, how to partition a scene into discrete objects) and the relationship between determination of depth and such partitioning were the primary focus of our discussions.

John Palmer (Assistant Professor of Psychology, U. of Washington) is also interested in the localization problem, from a mathematical psychology viewpoint. He visited here in December 1985 and we spent a day discussing the major problems in understanding localization. We plan to continue our dialog, exchanging manuscripts by mail and getting together at conferences. Palmer is particularly interested in how specific cues to depth are involved in localization, so his research and mine complement one another well.

Lawrence Arend (Eye Research Institute) visited SRI's vision group for six weeks in August and September of 1986. We had many useful conversations about the topics covered above and about possible areas to be explored.

Dr. Ben Kröse, a postdoctoral fellow at California Institute of Technology under Dr. Bela Julesz and Dr. David van Essen, and I worked on a joint project. He was at SRI for

two weeks in the summer of 1987 and we then continued the collaboration by phone, letter, and computer disks. Dr. Kröse and I investigated the effects of spatial interactions on rapid pattern discrimination. The results of this collaboration are reported in the manuscript included as Appendix C.

Dr. Donald H. Kelly and I completed and published some research on the early stages of spatial vision, which were reported in Kelly and Burbeck, 1987.

Dr. Dan Swift of the University of Michigan, Dearborn, visited for two weeks in Spring of 1988. We performed a methodological study on separation discrimination. The idea for the study, data for one observer, and a good understanding of the implications of the results were all completed during the two week visit. We are continuing our collaboration by phone and mail.

## PUBLICATIONS AND MANUSCRIPTS

- "Exposure-duration effects in localization judgments," *J. opt. Soc. Am. A* 3, pp. 1983-1988 (1986).
- "Position and spatial frequency in large-scale localization judgments," *Vision Res.* 27, 3, pp. 417-427 (1987).
- "Locus of spatial-frequency discrimination," *J. opt. Soc. Am. A* 4, pp. 1807-1813 (1987).
- "Further evidence for a broadband, isotropic mechanism sensitive to high-velocity stimuli," *Vision Res.* 27, 9, pp. 1527-1537 (1987), with D.H. Kelly.
- "Large-scale localization across spatial frequency channels," *Vision Res.* 28, pp. 857-859 (1988).
- "Eccentricity and separation effects in separation discrimination threshold," to be submitted to *Vision Research* . Included as Appendix A.
- "Role of local spatial filters in spatial-interval discrimination," to be submitted to *Vision Research* . Included as Appendix B.
- "Spatial interactions in rapid pattern discrimination," with Ben Kröse, to be submitted to *Spatial Vision*.. Included as Appendix C.
- "Perceived spatial frequency shift: origin and implications," under revision for *Vision Res.arch* . Included as Appendix D.
- "Form and separation," to be prepared for submission to *Vision Research*.
- "The remembered referent in separation discrimination and vernier alignment" with Dan Swift, to be prepared for submission to *Vision Research*.

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## **Appendix A**

### **ECCENTRICITY AND SEPARATION EFFECTS IN SEPARATION DISCRIMINATION THRESHOLDS**

To be submitted to *Vision Research*

To be presented at the Annual Meeting of the Optical Society of America, October 1988.

## **Eccentricity and Separation Effects in Separation Discrimination Thresholds**

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The contributions of eccentricity, separation, exposure duration and target size to the slope of the Weber function for length were systematically examined. Separation discrimination thresholds were measured for three separations, 2.9, 4.2 and 5.9 degrees, across a wide range of eccentricities. Over most of the range of eccentricities, and for all three stimuli, there was only a small effect of eccentricity, too small to account for the Weber function. The dependence of the threshold on exposure duration was determined using durations of 100 and 500 msec at 10 degrees eccentricity. The dependence of threshold on target size was measured using a length ranging from .17 to 1.3 degrees for a separation of 4.2 degrees in the fovea and from .5 to 2 degrees for separations of 2.8 and 10 degrees at 5 degrees eccentricity. Thresholds were little affected by either exposure duration or target size. Thus the spatial and temporal characteristics of the targets do not appear to be major factors controlling the slope of the Weber function. The foveally-centered Weber function was replicated for separations of 2.8 to 16 degrees with slopes of .9 and .8 on log-log coordinates for two observers. Separation discrimination thresholds measured for stimuli presented on isoeccentric arcs at 2.5, 5 and 10 deg show that the Weber function for length is largely dependent on separation for separations less than about 5 degrees. At separations larger than this, it is largely dependent on eccentricity. The 2.5 degrees data do not show a flattening, indicating that these spatial thresholds do not scale. These data suggest that there is a separation-dependent mechanism which dominates the central 5 degrees and an eccentricity-dependent mechanism which may be used mainly in the periphery.

## I. Introduction

To a first approximation, separation discrimination thresholds increase proportionally with separation, that is, the Weber function for length,  $\Delta s$  measured as a function of  $s$ , is linear on a log scale with a slope of approximately one. This is one of the fundamental properties of separation discrimination thresholds, and yet it remains unexplained. Because separation discrimination thresholds cannot, in general, be attributed directly to the responses of individual local spatial filters, the Weber function for length cannot simply be explained by observing that spatial uncertainty increases as spatial frequency decreases. An alternative explanation must be found. Levi, Klein & Yap (1988) have suggested that separation discrimination thresholds increase with increasing separation because in the usual experimental paradigm the stimuli are centered on the fovea, causing the retinal eccentricity of the individual targets to increase with increasing separation (when the stimulus is foveally-centered, as it usually is). According to this view, as eccentricity increases, the local positional information gets poorer, resulting in a higher separation discrimination threshold.

Supporting this view are the results of experiments that they conducted in which separation discrimination thresholds were measured on an iso-eccentric arc, 10 degrees from the fovea. They found little variation in threshold with separation, for separations ranging from 3.5 to 10 degrees, and concluded that the shape of the Weber function for localization was actually a simple consequence of retinal inhomogeneity.

However, Palmer and Murakami (1987) and Burbeck (1988) independently reported that if the separation is held constant and the retinal eccentricity varied, then separation discrimination thresholds change very slowly, far too slowly to account for the increase in threshold with increasing separation that is found with foveally centered targets. Specifically, if eccentricity were responsible for the shape of the Weber function for length then the threshold for a fixed separation should increase with increasing eccentricity with the same slope. Instead Burbeck found that threshold increased only slightly if at all between 2 and 10 degrees eccentricity and then increased more rapidly at a rate that depended on the detailed spatial and temporal characteristics of the target. These data are shown below. Palmer and Murakami also reported small eccentricity effects.

Collectively the data present an intriguing anomaly: fix the eccentricity and vary the separation and the threshold is approximately constant (Levi, Klein & Yap, 1988); fix the separation and vary the eccentricity and the threshold is again nearly constant (Palmer, 1987 and Burbeck, 1988). Yet when both eccentricity and separation are varied, the threshold increases

proportionally with separation (Fechner, 1858; Volkman, 1858; Klein and Levi, 1985, 1987; Toet et al., 1987; Burbeck, 1987). In short, the sum of the two factors appears to be much larger than either alone. What is the explanation for this?

In the experiments described here we look systematically at the contributions of both eccentricity and separation to the slope of the Weber function for localization. We begin by showing the data described previously that show that eccentricity can have a very small effect on threshold. We then vary both separation and eccentricity and examine the role of exposure duration and target size on the slope of the Weber function. Finally, we measure separation discrimination on iso-eccentric arcs, as done by Levi, Klein & Yap (1988), but we cover a larger range of separations and eccentricities and make an important change to their experimental paradigm.

## II. Eccentricity Effects for Large Separations

We know from contrast sensitivity studies, that the effect of eccentricity depends on the spatial characteristics of the stimulus. High spatial frequency targets are more affected than are low, consistent with the fact that spatial resolution becomes coarser as eccentricity increases. Thus, when examining the effects of eccentricity on separation discrimination thresholds, one would expect to find different effects for different stimuli. Small separations, and large separations with high spatial frequency targets, would be substantially affected by increasing eccentricity because the small separations become less resolvable and the high spatial frequency targets become less detectable as eccentricity increased. On the other hand, large separations with low spatial frequency targets would be less affected by increasing eccentricity. We argue that the latter is a better indicator of the effects of eccentricity on separation discrimination thresholds, per se, because it by-passes limitations imposed at the more distal stages of visual processing. Just as low contrast reduces separation discrimination thresholds because of poor signal quality, so increasing eccentricity with a high spatial frequency stimulus or small separation degrades signal quality. Since the Weber function for length has a slope of nearly one for large separations with low spatial frequency targets (Toet et al., 1987 and Burbeck, 1987) and it is this phenomenon that we seek to explain, we focus on this condition.

### *Methods*

The stimuli were all generated on a CRT with a mean luminance of 90 cd/m<sup>2</sup> (Conrac Model 2400, 48.3 cm diagonal, 60 Hz noninterlaced frame rate, 512x512 pixels). For the first

experiment, the stimulus consisted of a pair of bars, each measuring 1.3 degrees horizontally x 1.1 degrees vertically, presented with an average vertical separation of 4.2 degrees. The stimuli were presented at 90% contrast with abrupt onset and termination for a duration of 500 msec.

To prevent the observer from using the edges of the display as cues to position, the position of the stimulus on the display was varied randomly from trial to trial within the range  $\pm 0.7$  deg. Also, the stimulus was centered horizontally on the display so that it was well away from the edges.

Eccentricity was varied by instructing the observer to fixate a small fixation dot that was optically superimposed on the display and visible at all times. The stimuli were presented to the temporal retina of the right eye.

The vertical separation between the targets varied from trial to trial to determine the separation discrimination threshold. The observer's task was to report whether the targets presented on a given trial were closer together or farther apart than the average separation that he had seen on previous trials. Practice trials at the beginning of each data collection session enabled the observer to learn the average separation.

The method of constant stimuli was used with fourteen separations. A run consisted of 154 trials, of which the first 14 were practice and were excluded from threshold calculations. As many as 15 runs were conducted for a given observer and eccentricity to ensure that practice effects did not affect the final results. We found no practice effects for either of our experienced observers in this task. Thresholds were calculated at the 84% correct level using a program which optimised the likelihood of the best-fitting cumulative normal function. This is equivalent to performing standard probit analysis. This program also generated the standard errors, which are shown.

## *Results*

The data for both observers are shown in Fig. 1. The data are plotted as a function of the average eccentricity of the middle of the target pair. (Recall that the stimulus was also jittered vertically by a random amount from trial to trial, so there was up to 0.7 degree variation in the vertical placement.) Thus, for example, at 0 deg eccentricity, the targets were actually at approximately 2 degrees retinal eccentricity. (At 0 deg eccentricity, no fixation dot was used. The observer was simply instructed to fixate the center of the display.)

Between 0 and 10-15 degrees eccentricity, eccentricity had at most a small effect. Beyond 15 degrees, larger eccentricity effects could be seen. Note that if eccentricity variation were responsible for the slope of the Weber function, then the threshold would have had to nearly double when the eccentricity doubled. This clearly does not occur.

To determine whether this insensitivity was specific to our choice of stimuli, we repeated this experiment with smaller stimuli and a briefer presentation, using two new separations. In these experiments, separation discrimination thresholds were measured with lines that were  $4.1 \times 50$  arcmin, presented for 200 msec. Separations of 5.9 and 2.99 degrees were used. Data for these two conditions and two observers are shown in Fig. 2a,b. The same pattern of results was evident. For eccentricities up to 10 degrees, there was at most a small effect of eccentricity. At larger eccentricities, thresholds began to increase by an amount that depended on the separation used. (Thresholds for the smaller separation were more affected by increases in eccentricity, as expected.) Over most of the range of eccentricities, and for all three stimuli, there was only a small effect of eccentricity. To account for the Weber function for localization, the slope of these data would have to be approximately one. The data do not begin to account for an effect of that magnitude.

### III. Spatial and Temporal Characteristics of the Targets

The data shown in Figs. 1 and 2a,b suggest that the effect of eccentricity is not strongly dependent on the spatial and temporal characteristics of the targets, provided a large separation is used. However, given the importance of the conclusion, we chose to conduct further tests of the effects of these parameters.

#### Exposure Duration Effects

For foveally centered stimuli, the slope of the Weber function is known to depend on the exposure duration (Burbeck, 1986; Yap, Levi & Klein, 1987). The threshold at small separations is higher for an 100 msec exposure duration, than for a 500 msec or 1 sec duration, thus the slope is shallower for brief durations than for long. To understand more about the temporal factors contributing to the slope of the Weber function for length, we measured separation discrimination thresholds at 10 degrees using two exposure durations and a range of separations. The targets were the same as in the first experiment ( $1.3 \times 1.1$  deg bars). Data from this experiment are shown in Fig. 3a,b. For observer CAB, there was no significant effect of exposure duration. For observer JGP, the function was actually shallower for 500 msec than for 100 msec. We have no explanation for this effect. At an eccentricity of 10 degrees, exposure duration hardly affected the slope of the Weber function for both observers. For foveally centered targets, it affects the slope only at very small separations ( $< 20$  arcmin). Thus, exposure duration does not appear to be a major factor controlling the slope of the Weber function.

### Target Size

We now turn to the spatial domain to determine whether target size is an important contributor to the Weber function for length. We measured separation discrimination thresholds across the fovea with an average separation of 4.2 degrees. The height of each bar was scaled with its length in the 1.3 to 1.1 ratio used previously (which was dictated by the display and therefore arbitrary). The bars ranged in length from 0.17 to 1.3 degrees. Exposure duration was 500 msec. All other details of the experiment were unchanged from the previous experiments. Results are shown in Fig. 4. There was no systematic effect of target size for either observer. Thus, the eccentricity effects shown in Fig. 1 were not made artificially small by our use of a large stimulus. A smaller stimulus did not result in lower thresholds at small eccentricities. In short, we were not limiting performance at small eccentricities by choosing a stimulus that was advantageous to the periphery.

We also tested the effect of stimulus size using 4 arc min wide lines, varying only the length from .53 to 2 degrees. Measurements were made for two separations: 2.8 degrees and 10 degrees, centered at 5 degrees eccentricity. Exposure duration was 150 msec. The data are shown in Fig. 5. Over the ranges tested, target size clearly was not an important factor in determining the slope of the Weber function. The basic fact that separation discrimination thresholds increase almost proportionately with separation is a robust one. Changes in the spatial and temporal characteristics of the targets do not substantially change that relationship.

### **IV. Effects of Separation on Iso-Eccentric Arcs**

The data shown in Figs. 1 and 2a,b show thresholds increasing only slightly as the eccentricity is changed from 2 to 10 degrees. This suggests that, at least in that range, separation is the primary determinant of the slope of the Weber function for localization. To extend our understanding of how separation and eccentricity contribute to judging length for a larger range of separations, we measured separation discrimination thresholds for stimuli centered about the fovea and for stimuli presented on iso-eccentric arcs at 2.5, 5 and 10 degrees eccentricity. The stimuli were presented for 150 msec (for consistency with Levi, Klein and Yap, 1988).

Fig. 6 shows that for separations of 2.8 to 16 degrees, the foveally-centered Weber function follow Weber's law closely; slopes of .9 and .8 on log-log coordinates were obtained for observers YLY and AM respectively. Data for thresholds obtained with stimuli presented on iso-eccentric arcs are shown in Fig. 7a,b for the same observers. For most separations, thresholds increase markedly with separation under these iso-eccentric conditions. Thus for these separations

and eccentricities, separation is the primary factor contributing to the slope of the Weber function.

These data also suggest the existence of another process. At 5 and 10 degrees eccentricity, for separations larger than 5 and 10 degrees respectively, the Weber function becomes essentially flat. That is, in these regions the separation discrimination thresholds are independent of separation and depend only on eccentricity. This flattening is roughly consistent with the data reported by Levi, Klein and Yap. However they found that the bisection threshold improves rather than remaining constant at 10 degrees eccentricity for separations ranging from 3.5 to 10 degrees. There are significant differences between our experiments and theirs that may account for this discrepancy. Most important is the fact that Levi, Klein and Yap used a bisection task in which the eccentricity of the middle dot in their stimulus decreased as the separation increased. Thus any increase in the threshold due to an increase in the separation could have been concealed by a decrease in the threshold due to the decrease in the eccentricity of the middle dot.

Let us consider in more detail the 2.5 degrees eccentricity data for two observers shown in Fig. 8. At this eccentricity the Weber function does not flatten, although its slope does decrease as separation increases. Separation is the primary factor over the entire range of separations tested. (The maximum separation that can be tested at a given eccentricity is equal to twice the eccentricity.) If this pattern also holds for even smaller separations, as seems plausible, then one must conclude that separation itself is the primary determinant of the slope of the Weber function for length, being dominant over most of the normally measured range of separations and eccentricities.

## V. Discussion

The data presented here suggests that the Weber function for length is largely dependent on separation for separations less than about 5 degrees. At larger separations it is largely dependent on eccentricity. The switchover occurs at a separation roughly equal to the eccentricity of the targets. Thus there is an important interaction between separation and eccentricity. That the 2.5 degrees data do not show a flattening indicates that these spatial thresholds do not scale. These data suggest that there is a separation-dependent mechanism which dominates the central 5 degrees and an eccentricity-dependent mechanism which may be found only in the periphery. Alternatively, the eccentricity-dependent mechanism, modelled as a ruler limited by the spatial grain of the striate cortex (Levi, Klein and Yap), may be found in both central and peripheral vision but could have an internal noise level which exceeds that of the separation-dependent mechanism for separations less than 5 degrees.

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### Figure Captions

- Fig.1 Separation discrimination thresholds plotted as a function of eccentricity for a separation of 4.2 degrees for observers JGP and RLW. Thresholds show little dependence on eccentricity up to 10 or 15 degrees. For larger eccentricities, the eccentricity effect was pronounced.
- Fig.2 Separation discrimination thresholds plotted as a function of eccentricity for a separation of 2.9 degrees (a) and 5.9 degrees (b) for observers JGP and RLW. For the separation of 2.9 degrees, thresholds were constant up to 10 degrees eccentricity and increased for larger eccentricities. For the separation of 5.9 degrees, thresholds showed a slight dependence on eccentricity at all eccentricities for observer RLW but a steeper slope for eccentricities greater than 15 degrees for observer JGP.
- Fig.3 Separation discrimination thresholds plotted as a function of separation for exposure durations of 100 and 500 msec at an eccentricity of 10 degrees for observers CAB (a) and JGP (b). Observer CAB did not show any significant difference between the two exposure durations. Observer JGP showed a flatter slope with the 500 msec duration than the 100 msec duration.
- Fig.4 Separation discrimination thresholds plotted as a function of target length for rectangular targets with a height to length ratio of 1.3 to 1.1 for a foveally-centered separation of 4.2 degrees and an exposure duration of 500 msec for observers JGP and RLW. There was no systematic dependence on target size for either observer.
- Fig.5 Separation discrimination thresholds plotted as a function of target length for bars of width 4 arc min. Thresholds were measured for separations of 2.8 and 10 degrees at an eccentricity of 5 degrees and an exposure duration of 150 msec. Thresholds showed very little improvement with increasing length.
- Fig.6 Separation discrimination thresholds for foveally-centered targets plotted as a function of separation on log-log axes for observers YLY and AM. The slopes of the best-fitting

lines were .9 for observer YLY and .8 for observer AM, which follow Weber's Law behaviour closely.

Fig.7 Separation discrimination thresholds plotted as a function of separation at eccentricities of 5 and 10 degrees for observer YLY (a) and at eccentricities of 2.5, 5 and 10 degrees for observer AM (b). For both observers, thresholds show a dependence on separation for separations smaller than 5 degrees. However, for separations larger than 5 degrees at 5 degrees eccentricity, and larger than 10 degrees at 10 degrees eccentricity, threshold becomes a constant function of separation, depending only on eccentricity.

Fig.8 Separation discrimination thresholds plotted as a function of separation at an eccentricity of 2.5 degrees for observers AM and PA. Thresholds increase with increasing separation for all separations, although the slope decreases slightly for separations greater than 2 degrees.

FIGURE 1

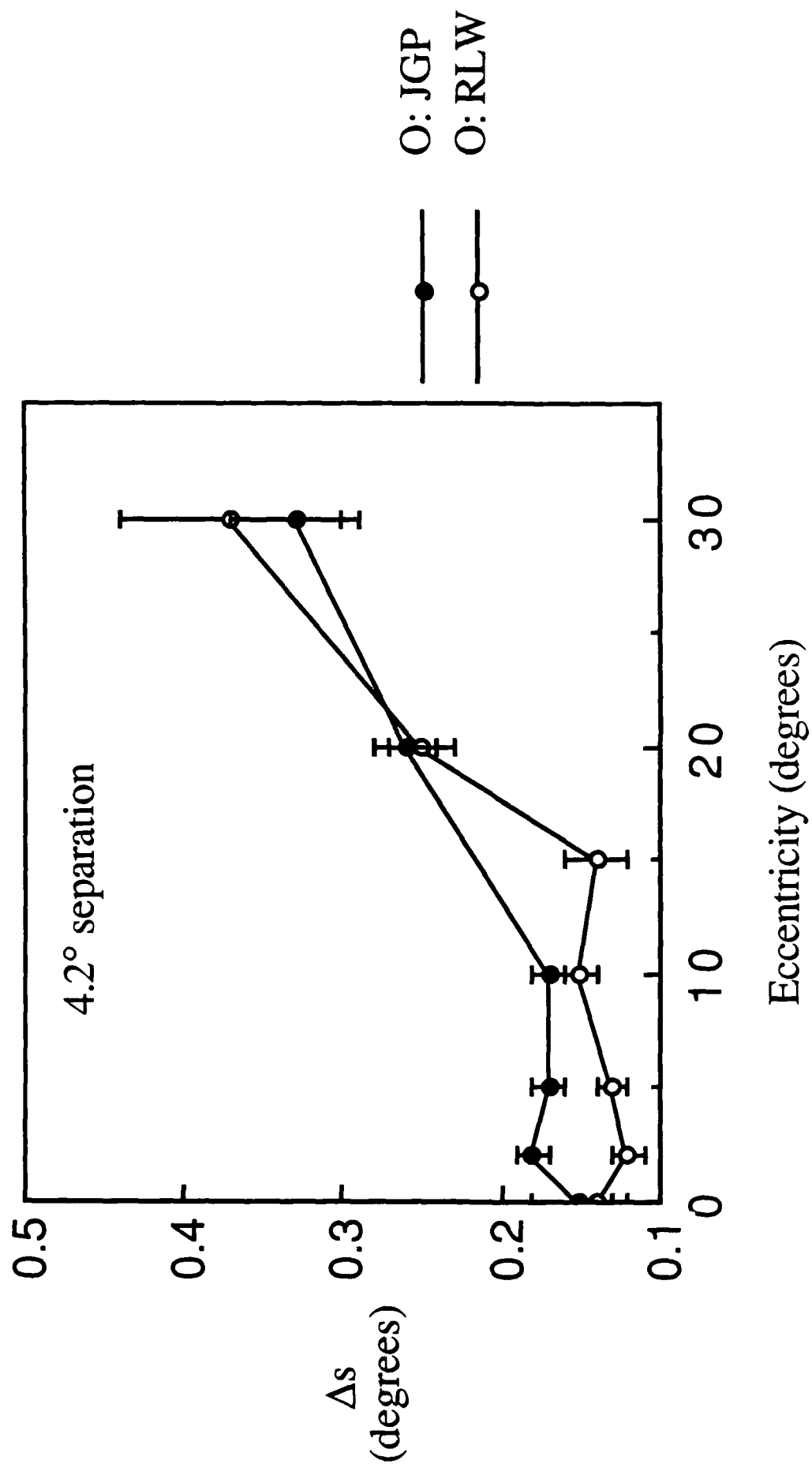
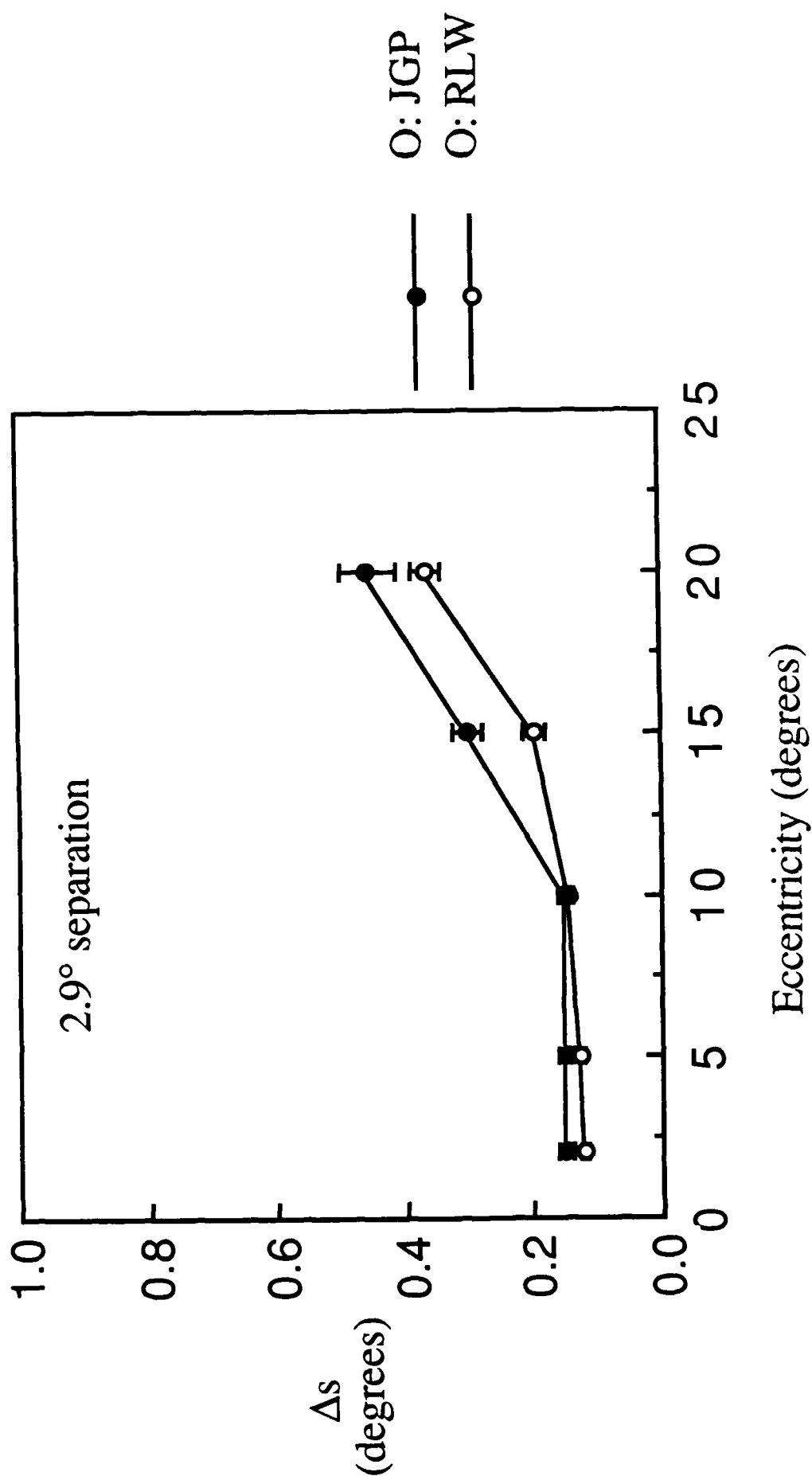


FIGURE 2a



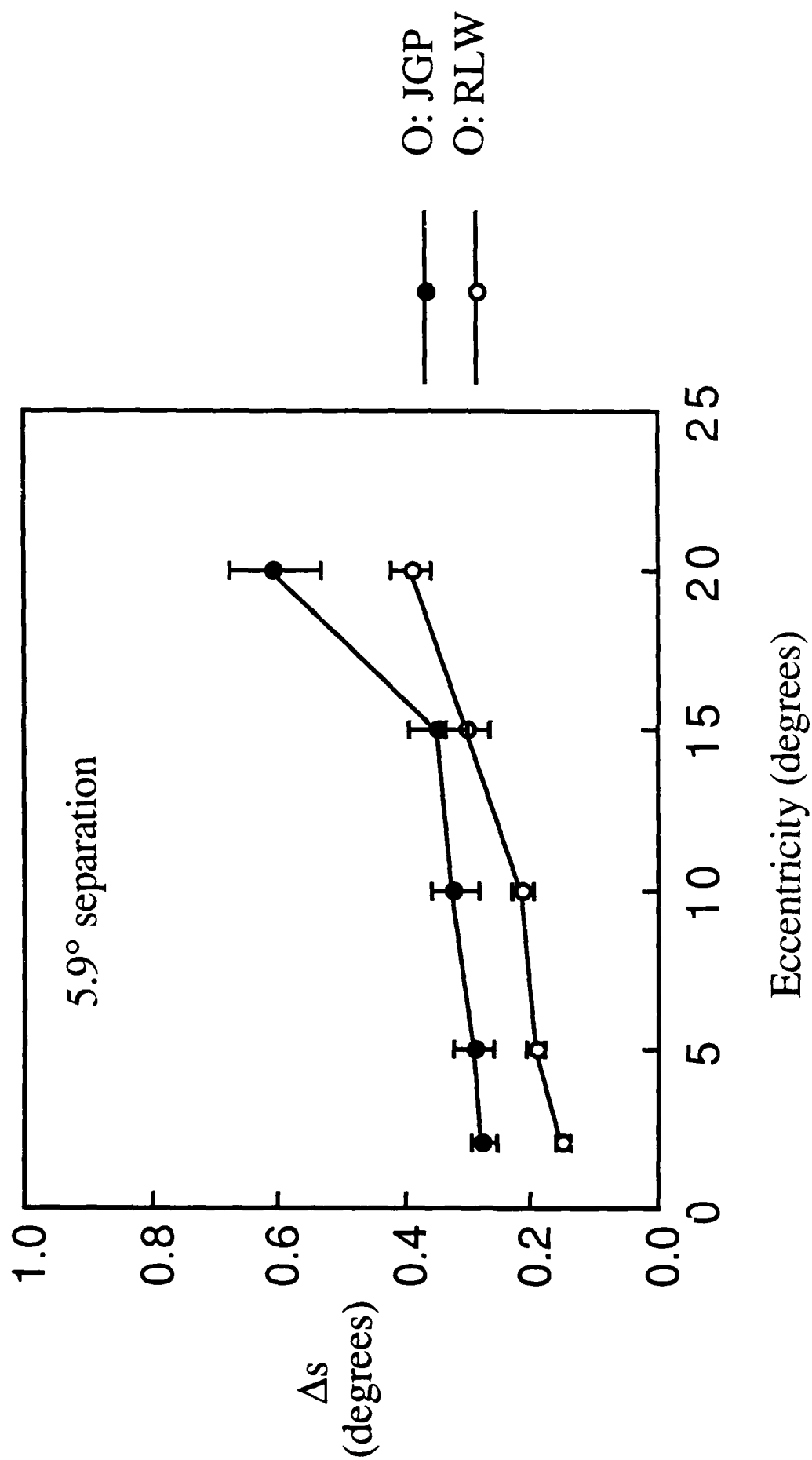
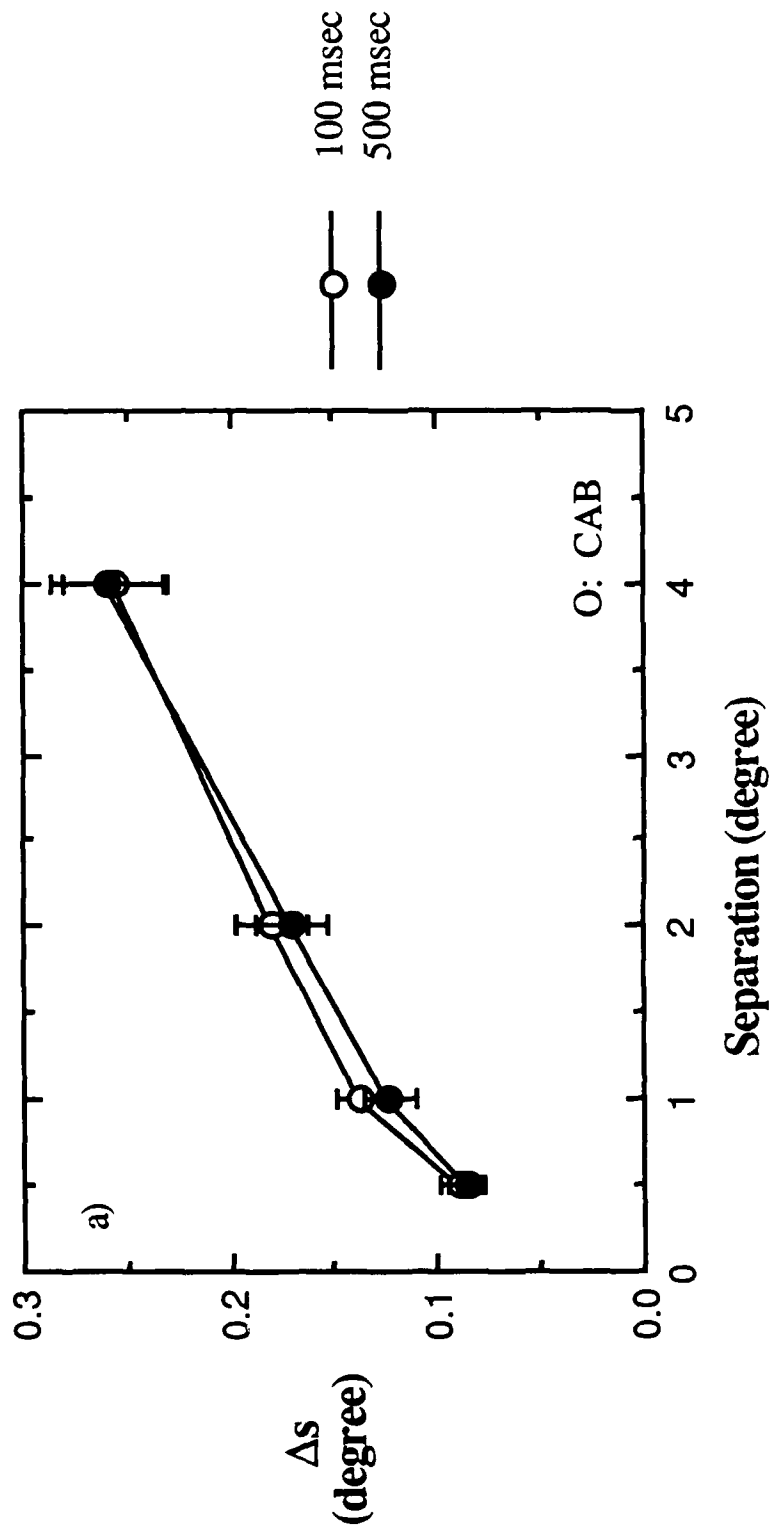
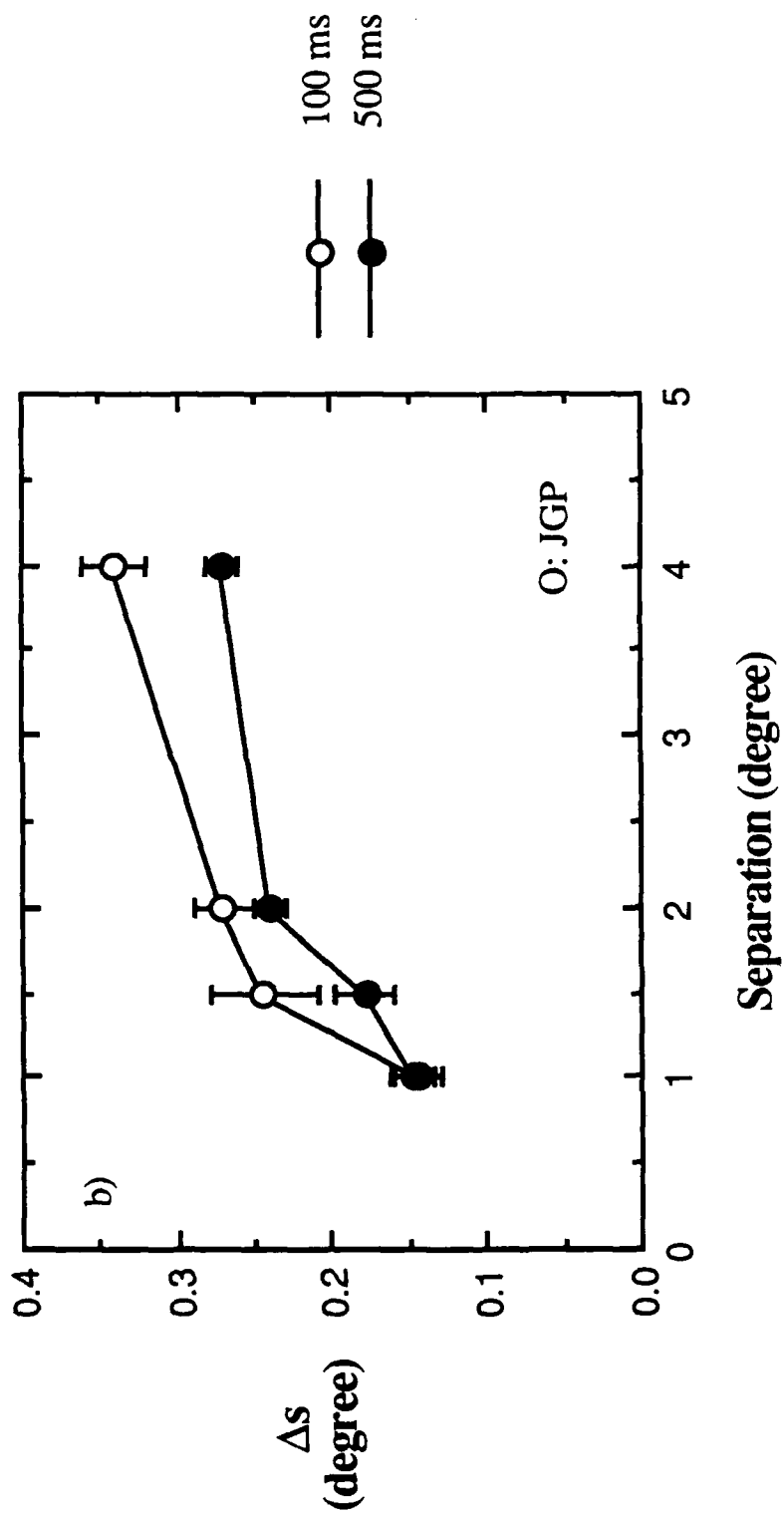
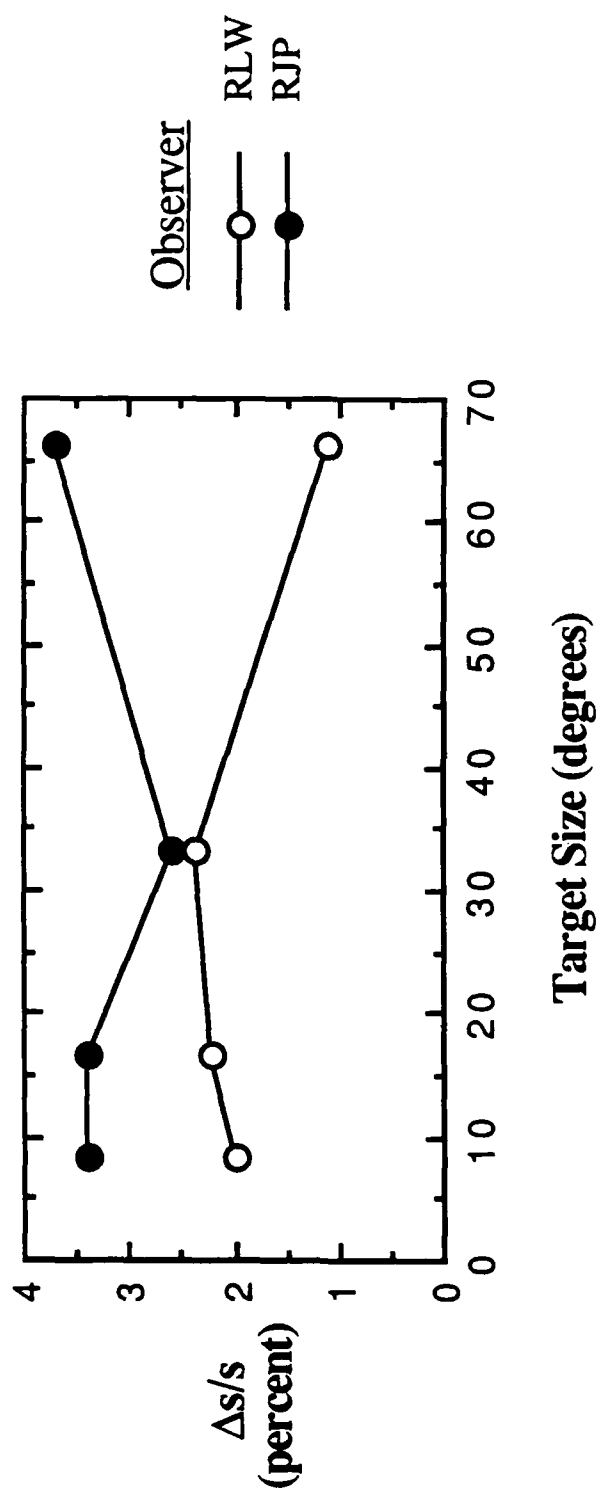
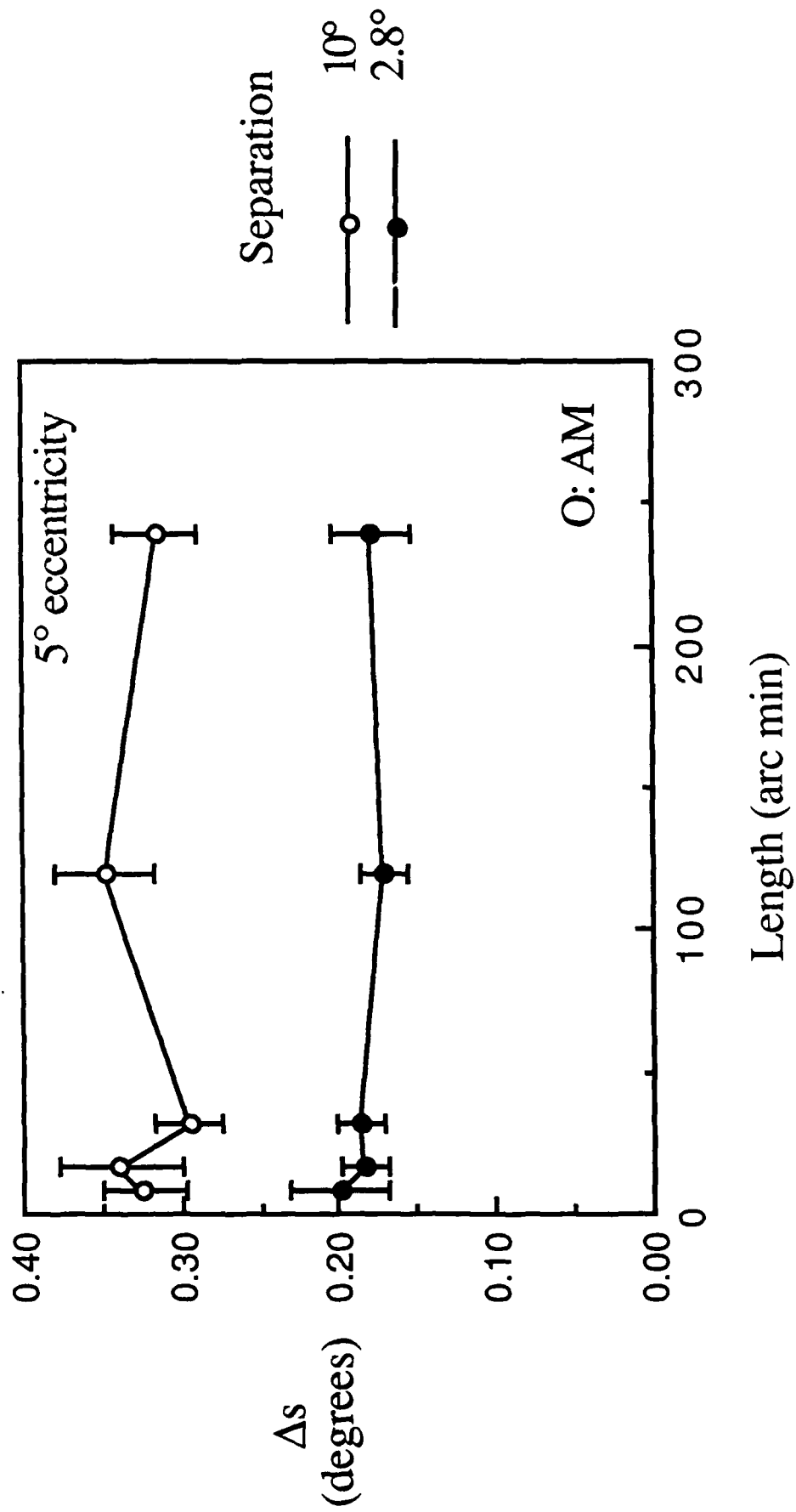


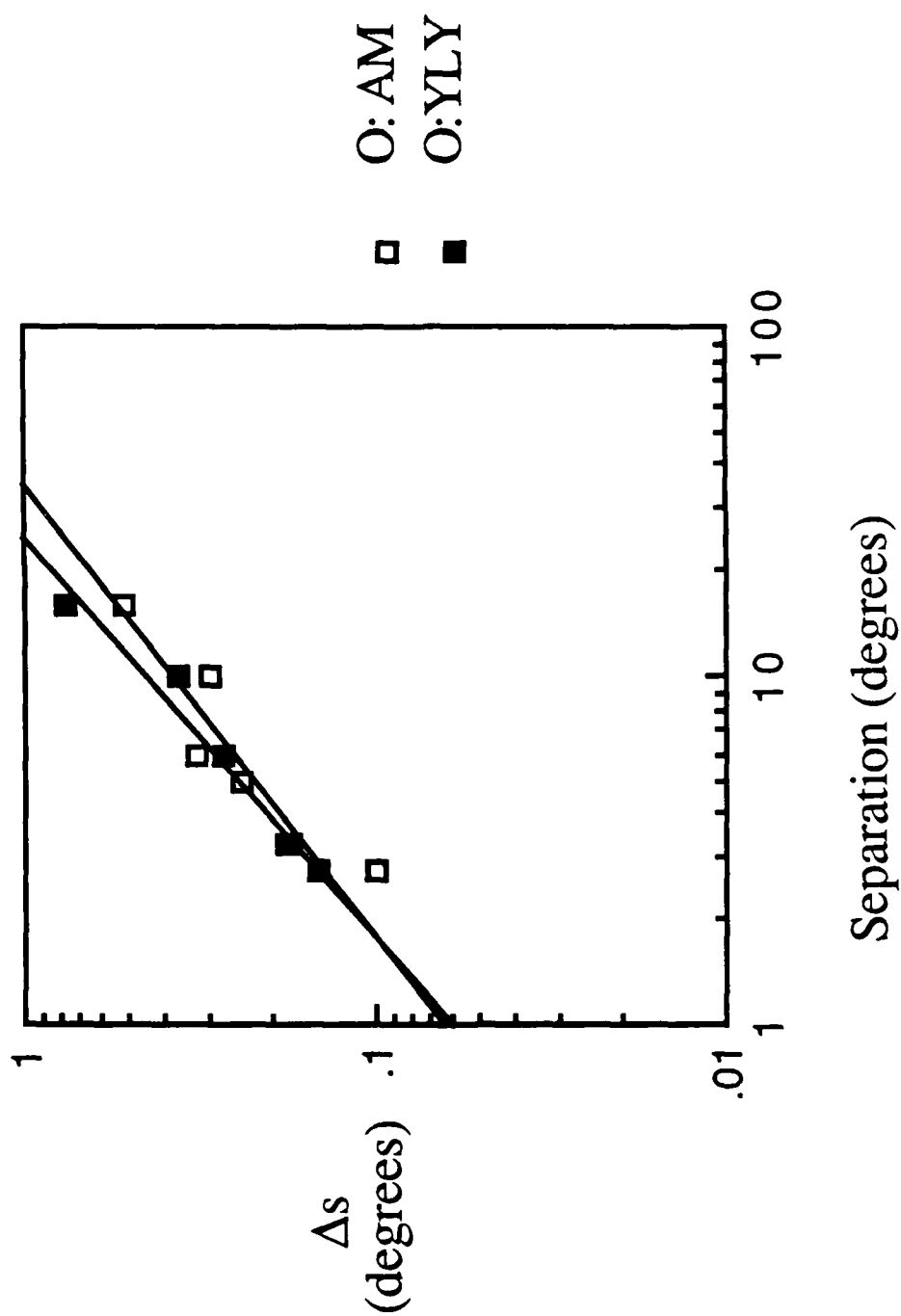
FIGURE 3a

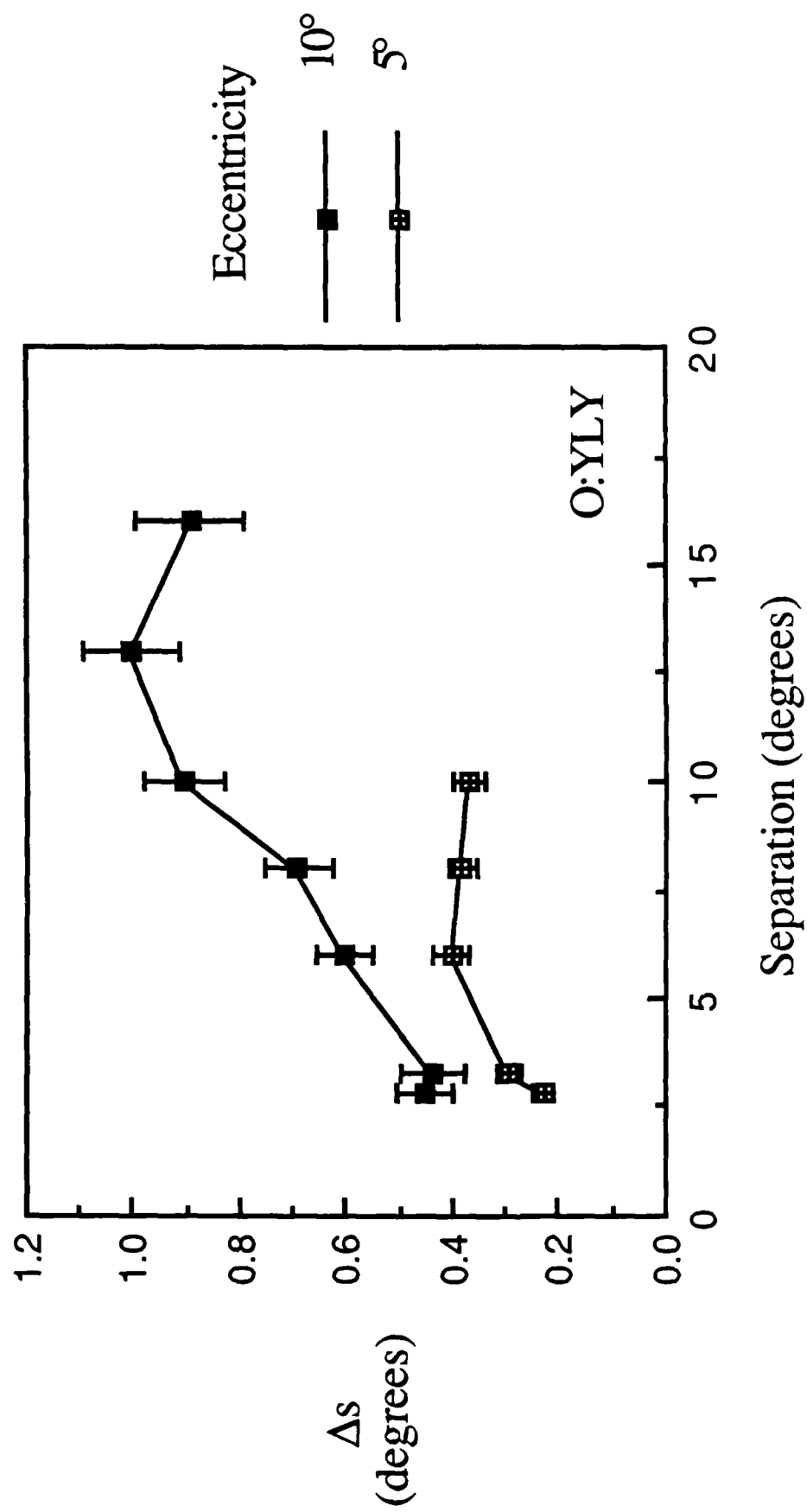












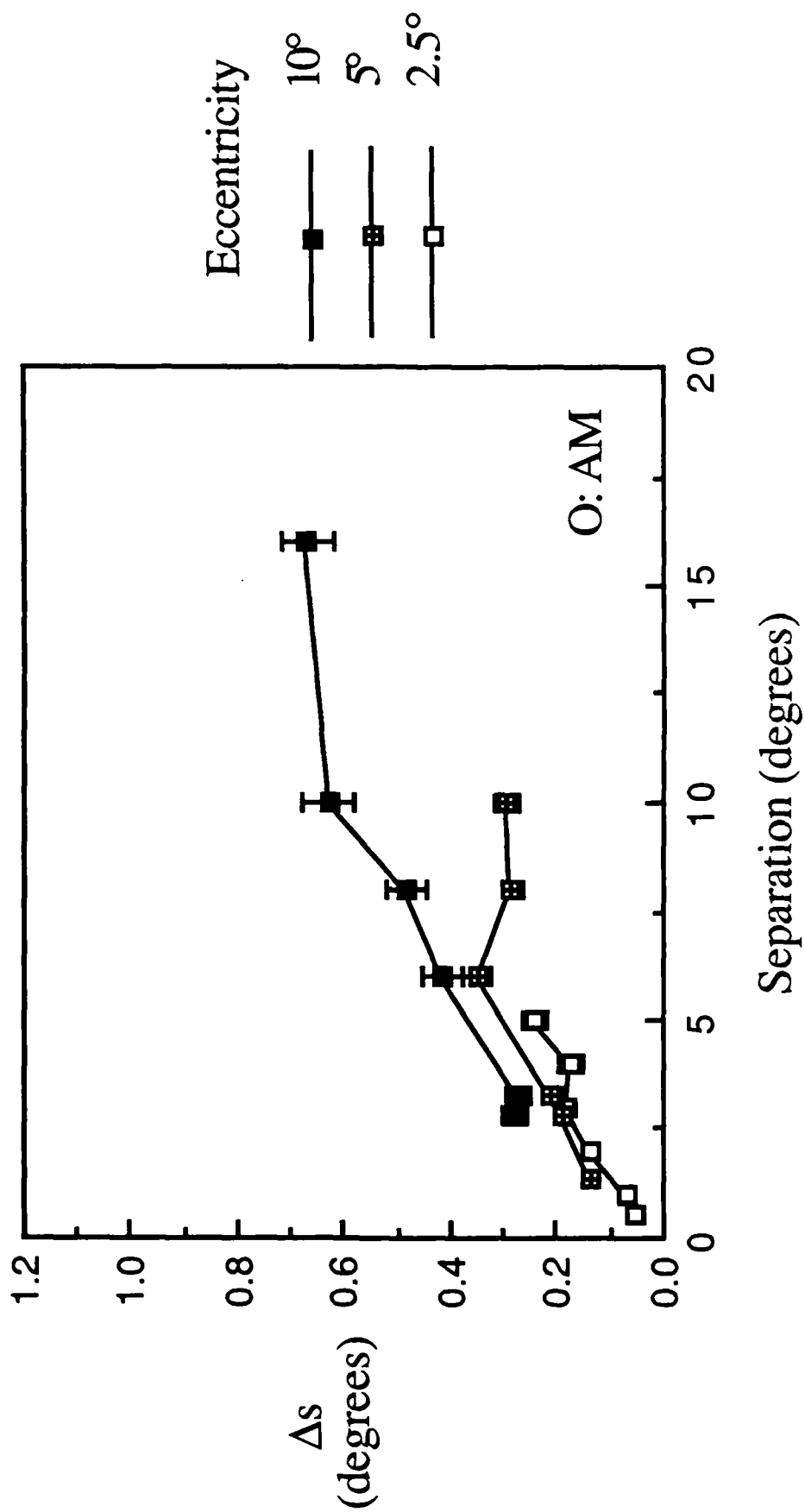
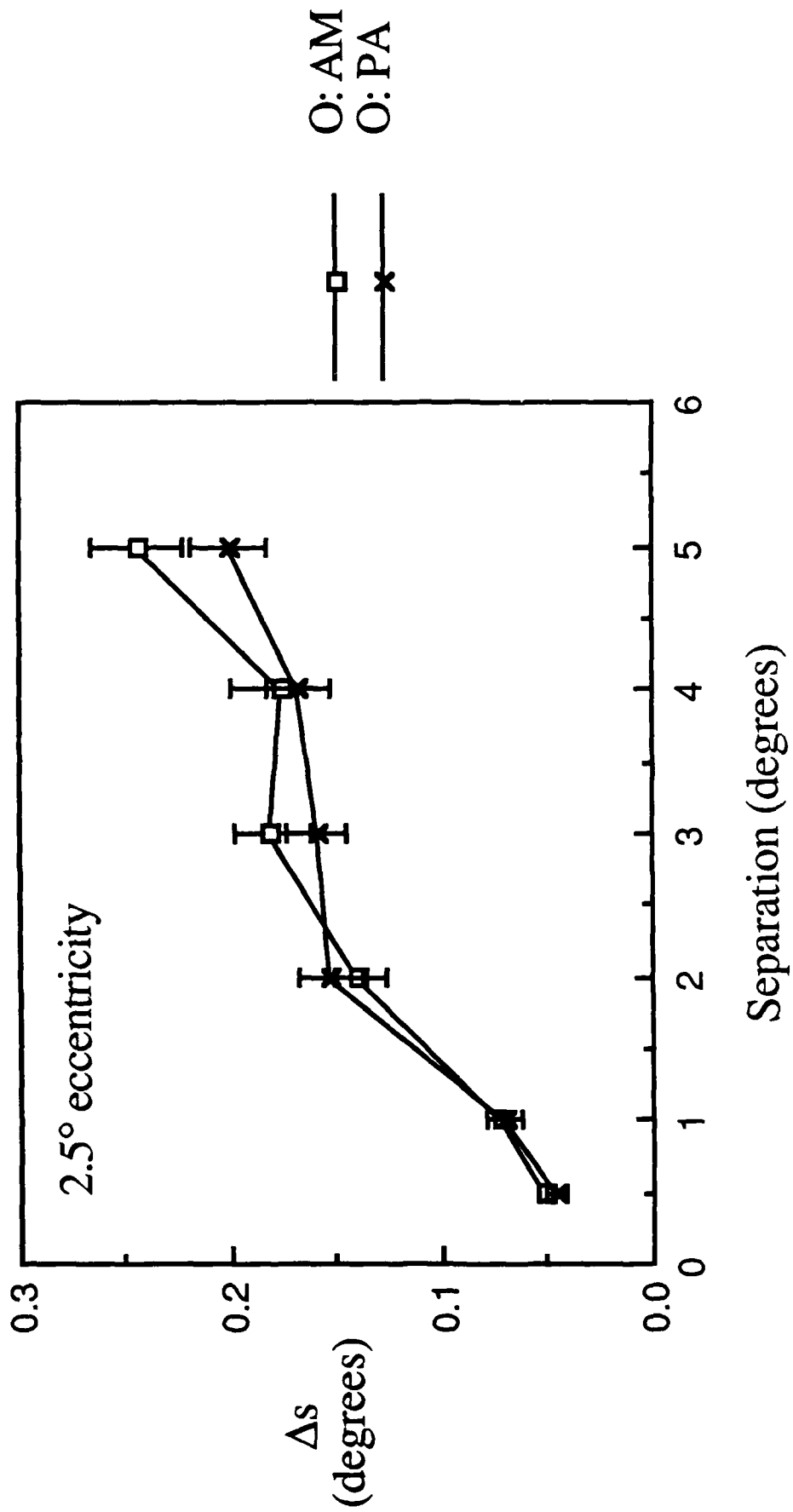


FIGURE 8



## **Appendix B**

### **ROLE OF LOCAL SPATIAL FILTERS IN SPATIAL-INTERVAL DISCRIMINATION**

Draft to be Submitted to *Vision Research*

## **Role of Local Spatial Filters in Spatial-Interval Discrimination**

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Spatial-interval discrimination thresholds are measured for a pair of bars in the presence of other parallel bars placed far enough from the targets as to be outside the range of neural and optical blurring. Thresholds are elevated when the targets are embedded in an array of four parallel bars (two between and two flanking the targets), but they are not elevated when there are two parallels between the target bars, or when two parallels are flanking the target pair. The threshold elevation is larger with a 100-ms exposure duration than with a 500-ms exposure duration. Attenuating the high spatial frequencies magnifies this effect. Data are also obtained on the effect of flanking distance. They support the conclusion that the spatial filters involved when the targets are crowded are tuned to higher spatial frequencies than are those involved when the targets are presented on a uniform field. Collectively, the data indicate that the mechanism responsible for spatial-interval discrimination can select which spatial filters to use, using lower-spatial-frequency filters when they provide good information and switching to higher-spatial-frequency filters when the lower spatial frequency filters are no longer useful.

## INTRODUCTION

Much research on spatial-interval discrimination has focused on attempts to explain the phenomenon in terms of the responses of individual local spatial filters, for example those postulated by Wilson and Bergen (1979) or Watson (1982). The idea has been that the spatial filters themselves carry the information about the size of the spatial interval. In this model, large intervals are indicated by activity at low spatial frequencies, small intervals by activity at high spatial frequencies, and so forth. However, considerable evidence against this approach has recently been presented. Toet et al. (1987) and I (1987) independently showed that manipulating the spatial frequency content of the stimulus has no effect on the interval judgment. Accuracy is as high for a pair of high-spatial-frequency targets as for a pair of low-spatial-frequency targets, even when the separation between the targets is so large that the high-spatial-frequency targets could not possibly be seen by the same spatial filter. In addition, I have shown that spatial-interval discrimination thresholds are also unaffected if one of the targets stimulates only high spatial frequencies and the other only low (Burbeck, 1988).

Collectively, these data suggest that the mechanism responsible for spatial-interval discriminations uses information from the local spatial filters to determine the positions of the individual targets. In short, the "length gauge" follows the local spatial filters. (The spatial-interval discrimination mechanism is referred to here as the "length gauge" for brevity, specifically without the implication that the mechanism has the properties of any specific type of length gauge).

All of the experiments in the studies discussed above used targets presented on uniform backgrounds. For such stimuli, any responding spatial filters could potentially provide useful information; the length gauge does not have to select among filters. Thus, these experiments leave open the question: of whether the length gauge is able to select which filters to use, or whether it responds automatically to any stimulation present?

Watt (1985) has suggested that a choice is made. Specifically, he suggests that when the targets are presented on a uniform background, the length gauge uses the filter with the lowest spatial frequency possible because it has the highest signal-to-noise ratio. However, when other objects are near the targets, the low-spatial-frequency filters respond to the other objects as well, and so yield unreliable information. In that case, a filter tuned to a higher spatial frequency provides better information, despite a generally lower signal-to-noise ratio, because of the smaller receptive field size. Morgan and Ward (1985) provide some experimental support for this view in

their study of the effects of parallel flanking lines on spatial-interval discrimination for lines separated by a few (3, 6 or 12) arcmin. They find no effects of flanking lines that are sufficiently far from the targets to eliminate optical or neural blur and conclude that the spatial filters responsible must be very small indeed (too small to detect both targets simultaneously). However, Morgan and Ward do not provide compelling evidence that larger filters are employed in the absence of the flanking lines. Thus, it is still not clear whether the length gauge can choose the best filter.

The experiments reported here test this hypothesis using a large separation. Use of the large separation increases the range of spatial frequencies that carry pertinent information and makes it easier to determine whether the addition of flanking lines is changing the range of spatial frequencies used in the discrimination task.

Three techniques are used to determine which spatial frequency ranges are carrying the relevant information: attenuating middle and high spatial frequencies using a diffusion screen; varying the exposure duration (from 100 to 500 ms); and varying the distance between the flanking lines and the targets. Attenuating middle and high spatial frequencies by a diffusion screen shows directly the role of those frequency ranges in the determination of threshold. The exposure duration effect is more subtle. I have shown previously that, for durations longer than about 100 ms, the effect of exposure duration on spatial-interval discrimination thresholds depends on which spatial-frequency range is carrying the relevant information. When high spatial frequency range is in use, effect is large and statistically significant. When the relevant spatial frequency range is low, exposure duration had little or no effect. This is true regardless of the interval size. With the large intervals and bar targets used in the experiments reported here, exposure duration has a small effect at most when the targets are presented on a uniform field (Burbeck, 1986). If the addition of flanking lines causes the exposure duration effect to increase, then it is plausible that higher spatial frequencies are being used in the presence of the flanking lines than were used in their absence. Finally, I manipulate the distance between the flanking lines and the targets to assess the spatial range of the effect of the flanking lines.

## METHODS

Spatial-interval discrimination thresholds were measured using the method of constant stimuli. On each trial, a single stimulus was presented and the observer was asked to report whether the target bars in that stimulus were closer together or farther apart than the average

separation that he had seen on previous trials. The target separations (measured center-to-center) ranged from  $2.77^\circ$  to  $3.07^\circ$ . The average separation was  $2.92^\circ$ .

The target and parallel bars each subtended  $11.3^\circ$  horizontally and  $0.34^\circ$  vertically. They were presented at 45% (Michelson) contrast on a  $90 \text{ cd/m}^2$  background. The exposure duration of the target and parallel bars was a parameter of the individual experiments. The target and parallel bars were white; the parallels were white.

The exact distance of each parallel from the nearest target was determined randomly from trial to trial within the range 46 to 72 arcmin (center to center). A range of distances to the parallels was used so that the distance between the parallels themselves (in particular, between the inner parallels) would not yield information about the target separation. The range that was used places the parallels outside the range of optical and neural blurring, as indicated by data on the effects of flanking lines on vernier acuity (Levi et al., 1985) and on bisection (Yap et al., 1987). They found that for retinal eccentricities less than about  $2.5^\circ$ , flanking lines have no effect when the distance between the target and flanking line exceeds 25 arcmin. Our target lines were seen at an average eccentricity of  $1.46^\circ$  (half of the  $2.92^\circ$  separation) and were always more than 25 arcmin (edge to edge) from the nearest target, so any effects of our parallels cannot be attributed to the same lateral interactions that affect vernier acuity and bisection thresholds.

The stimuli were presented with abrupt temporal onsets and terminations. Several exposure durations were used: 102, 255, and 510 ms and a response-terminated condition.

Our stimuli were displayed on a high-resolution monitor, which was controlled by a microcomputer. Details of this display are given elsewhere (Burbeck, 1986). The display subtended  $14.4^\circ$  horizontally and  $10.6^\circ$  vertically at the 155-cm viewing distance. The position of the stimulus was varied randomly from trial to trial relative to the upper and lower edges of the display (within the range  $\pm 19.3$  arcmin relative to the centered position) to prevent the edges of the display from providing useful position cues.

Data were collected in sessions of 84, 154, or 294 trials (depending on the endurance of the observer); the first 14 trials in each session (which constituted the first block of stimuli) were practice and were not included in the data analysis. At least 210 nonpractice trials were conducted for each condition and each observer. Data were analyzed by standard probit analysis techniques (Finney, 1971). A total of five observers were used. All had normal or corrected-to-normal vision. Viewing was monocular, unless indicated otherwise.

## RESULTS

### Embedding the Targets in an Array of Four Parallel Bars

In these experiments, spatial-interval discrimination thresholds were measured with the target bars embedded in an array of four parallel bars, as shown in Fig. 1a. Spatial-interval discrimination thresholds were also measured using just the target bars, with no extraneous parallels. These control data were obtained under the same experimental conditions in interleaved sessions with the four-parallel bars data. One-dimensional Fourier transforms of these two stimuli are shown together in Fig. 2. The lowest peak in the Fourier Transform of the targets is the separation frequency, that is, the reciprocal of the average distance between the targets. Addition of the parallel bars outside the target bars masks activity at this frequency. The addition of the parallel bars between the targets adds noise at moderate spatial frequencies, particularly 0.5 to 2 cycles/degree. In the Fourier transform, this leaves only the higher spatial frequencies of the target lines to convey the position information. However, neurons in the visual system do not have infinitely extensive receptive fields, so the Fourier transform is somewhat misleading. Instead, it is probable that the receptive field size of the local spatial filters decreases with increasing spatial frequency. If that is true, then, the smaller receptive fields of middle- and high-spatial-frequency filters will make them unaffected by the parallel bars. Thus, if the length gauge can select the best filter, then it should select a middle or high spatial frequency when the targets are embedded in four parallel bars, and it should select a lower-spatial-frequency when the targets are not flanked by other bars, because a lower-spatial-frequency filter has a lower signal-to-noise ratio. The best frequency range in each case depends on the sensitivities and bandwidths of the local spatial filters.

If the length gauge does choose the best filter, then at short exposure durations, thresholds for the four-parallel bars condition should be elevated relative to the no parallel condition. At longer exposure durations, however, the threshold with parallels should return approximately to the value obtained with no parallel bars. Previous research has shown that, for long exposure durations, spatial-interval discrimination thresholds are equal whether based on low- or high-spatial-frequency information (Burbeck, 1987). However, the addition of parallel bars would be expected to add some overall noise to the system. Thus, the key issue here is not whether the parallel bars elevate threshold at all, but whether the effect of exposure duration is increased by the addition of the parallels.

Data were collected for three subjects and a range of exposure durations. The data are shown in Fig. 3 a, b, and c. The data for the targets with no parallel bars show no effect of exposure duration, consistent with previous reports using large separations (Burbeck, 1986). However, when the targets are embedded in four parallel bars, there is a significant exposure duration effect. Thresholds are substantially elevated at 100 and 255 ms durations, and are elevated only slightly or not at all at the longest duration used (response-terminated). This is consistent with the hypothesis that the relevant spatial frequency range has been increased by the addition of the parallel bars.

To test further the hypothesis that the visual system is using higher spatial frequencies to make the spatial-interval discrimination judgment when the targets are embedded in four parallel bars, we attenuated those higher spatial frequencies using a diffusion screen placed in front of the display monitor.

#### **Spatial-Interval Discrimination with Middle and High Spatial Frequencies Attenuated**

The spatial frequency characteristic of the diffusion screen was calibrated by measuring contrast sensitivities for horizontal sinewave gratings with and without the screen in place. Contrast thresholds were measured using a standard yes/no staircase procedure. Eight pairs of contrast reversals from two interleaved staircases were averaged to yield an estimate of contrast threshold. The horizontal gratings subtended  $12.4^\circ \times 9.1^\circ$  and were presented for 100 ms. Other experimental conditions were the same as for the other experiments.

The ratios of the contrast thresholds obtained with and without the diffusion screen in place are plotted in Fig. 4 for two observers. Spatial frequencies higher than 1 cycle/degree are severely attenuated by the diffusion screen. Thus, the threshold for the unflanked stimulus should be relatively unimpaired if spatial-interval discriminations are performed on the basis of responses of spatial filters tuned to low spatial frequencies, as the lack of exposure-duration effect suggests. However, the thresholds for the flanked stimulus should be significantly affected because they are controlled by the responses of filters tuned to higher spatial frequencies, which are severely attenuated by the diffusion screen.

Spatial-interval discrimination thresholds were measured for two observers with and without the diffusion screen in place. The ratio of these two thresholds, which is a measure of the effect of the diffusion screen itself, is shown in Fig. 5. There is a small significant effect of the

diffusion screen in the no-parallels case for one observer at 100 ms exposure duration. Otherwise there was no significant effect in the no parallels case. However, in the four-parallels case, there was a significant effect for both observers which was large at the short exposure duration. In fact, the datum for Observer LMT at 100 ms is only a lower estimate. Threshold could not be determined accurately because the range of separations needed could not be accommodated. (The parallel bars between the targets began to overlap when the range of separations was increased to the extent required to measure her threshold.)

These data support the idea that low spatial frequencies are used when parallels are absent and higher spatial frequencies are used when the parallels are present. In short, when the low-spatial-frequency filters do not provide good information, they are not used.

How low is the spatial frequency range that is used in the absence of parallel bars? Specifically, does the relevant spatial filter extend across the entire stimulus, detecting both targets? To test this possibility, we measured spatial-interval discrimination thresholds with two parallels, flanking the target pair, as shown in Fig. 1b or between the targets, as shown in Fig. 1c. If the relevant receptive field detects both targets then it must also detect these parallel bars. The two cases are considered individually.

### **Spatial-Interval Discrimination with Outside Parallel Bars**

This experiment was identical to the initial experiment reported above except that the bars between the targets were removed, as shown in Fig. 1b. It is similar to an experiment performed by Morgan and Ward (1985) using small separations.

Two exposure durations were tested, 100 and 500 ms. Data for two observers are shown in Fig. 6. Also shown for comparison are data obtained with no parallels. (The inside parallels will be discussed below). At the short exposure duration, the outside parallels elevated thresholds.

However, informal observation suggested that the outside bars appeared to create a reference frame that affected the perceived depth of the targets. As that reference frame changed from trial to trial, the perceived depth of the target bars changed. With that change in perceived depth came a change in perceived separation (Burbeck, 1986).

To test the validity of these observations, spatial-interval discrimination thresholds were measured again except with binocular viewing and dim room illumination to facilitate acquisition of depth information. If the outside parallels are affecting threshold by affecting perceived depth, then the changes should reduce or even eliminate the effect. Data for two new observers are

shown in Fig. 7. Data were obtained in interleaved sessions for the no-parallels and four-parallels conditions for comparison.

In the binocular condition, neither observer showed any effect of the outside parallels. For Observer CAB, the ratio of the outside-parallels threshold to the no-parallels threshold was 1.43 for monocular viewing and 0.96 for binocular viewing. For Observer MAC, the same ratio was 1.32 for monocular and 1.14 for binocular viewing. The absence of significant effect of the outside parallels for both observer confirms the observation that the outside parallels affected the perceived depth of the target bars with binocular viewing.

Thresholds for the four-parallels condition were unaffected by the change from monocular to binocular viewing. Thus, the effect of four parallels appears not to be due to changes in perceived depth. The original hypothesis that it results from a change in the relevant range of spatial frequencies remains valid.

### **Spatial-Interval Discrimination with Parallel Bars Between the Targets**

Spatial-interval discrimination thresholds were measured in the presence of parallel bars lying between the target pair, as shown in Fig. 1c. All other experimental conditions were the same as in the previous experiments. Thresholds were measured for exposure durations of 100 and 500 ms. The prediction for this stimulus is the same as for the stimulus with the parallel bars outside. Any spatial filter that detected both targets must also detect the inside parallels. Thus if spatial interval discrimination is based on the responses of such filters, accuracy must be impaired.

Figure 6 shows data for two observers. For one, there was a small threshold elevation in the presence of the inside parallels that did not vary with exposure duration. For the other observer, there was a small significant decrease in threshold at the 500-ms exposure. Overall, the addition of bars between the targets had little effect.

Two conclusions could be drawn from the data on the inside parallels and outside parallels. One is that the spatial filters used by the length gauge in the no-parallels case are the same as those used in the inside- and outside-parallels cases, and that those spatial filters detect the targets individually. Another possible conclusion is that the spatial frequency range used in the two-parallels cases is lower than that used when four parallels are present, but higher than that used when parallels are absent. To test this latter possibility, we examined the effects of the diffusion screen on the inside-only and outside-only conditions. If substantially higher spatial frequencies are involved in the two-parallels than in the no-parallels condition, then the diffusion

screen should affect results with two parallels more than those with no parallels.

The effects of the diffusion screen are shown in Fig. 8. Use of the diffusion screen does not create an exposure duration effect of the expected type for either the inside-only or outside-only conditions. These data support the conclusion that the same spatial filters are responsible for the no-parallels condition and for the inside-only and outside-only conditions. If that conclusion is correct, then we may also conclude that the relevant spatial filters detect the targets individually. That is, they do not directly encode the separation between the targets, but instead encode the positions of the individual targets. Given the large ( $3^\circ$ ) separation between the targets, this seems plausible.

### **Spatial Extent of the Parallel Lines Effect**

As the third line of attack on the question of which spatial filters are providing the information to the length gauge, I varied the distance between the targets and the parallels. To permit greater freedom of manipulation, the targets and parallels were changed from bars to narrow ( $2.6$  arcmin) lines. The length and contrast of the lines, and other details of the experiment were the same as before. In the previous experiments, the distance from each parallel to the nearest target ranged from  $0.77^\circ$  to  $1.2^\circ$  (measured center to center). In the present experiments, three ranges were tested:  $0.086^\circ$ - $0.52^\circ$ ,  $0.45^\circ$ - $0.88^\circ$ , and  $0.77^\circ$ - $1.2^\circ$ . Each range subtends  $0.43^\circ$ . Thus, the variability in the position of the parallel line was the same for each range, and the same as that used in the initial four-parallels experiments.

The results for two exposure durations are shown in Fig. 9. For the short exposure duration, the effect of the parallel lines is small for the smallest flank distance and significantly larger for the two larger distances. At the longer exposure duration, there is a small effect of the parallel lines that does not depend significantly on the distance to the parallels. Thus, the effect of exposure duration is small when the parallels are closest, becoming highly significant when they are farther away. Within that context, these data suggest that lower-spatial-frequency filters are involved when the parallels are close to the targets and higher-spatial-frequency filters are involved when they are farther away. (In another study, in which the positions of the parallels are specified on each trial, we find that their effect does decline when the distance to the targets grows sufficiently large.) This is compatible with the observer's perception. At small distances, the parallels and target group together and the judgment seems to be made on the average position of the cluster of three lines. When the parallel lines are farther away from the targets, the positions of

the target lines seem to be detected individually.

## DISCUSSION

The experiments reported here show that spatial-interval discrimination thresholds depend on the context within which the targets are placed. When the targets are embedded in an array of four parallel lines, the low spatial frequencies of the stimulus array no longer carry accurate information about the separation between targets. Under those conditions, spatial-interval discrimination thresholds are elevated, particularly at short exposure durations. The magnitude of the exposure duration effect and the threshold elevation that results when the middle and high spatial frequencies are attenuated by a diffusion screen indicate that, under these conditions, spatial-interval discrimination is being done on the basis of middle- or high-spatial-frequency information. However, for this information to be useful, it must be obtained locally. Such local processing is precisely what has been found physiologically and psychophysically, so this explanation is plausible.

The length gauge appears to use whatever spatial-frequency range provides the best information. For widely separated bars in an uncluttered field, lower spatial frequencies are best, but for such bars in a cluttered field, higher spatial frequencies are preferred. However, information about the interval itself is not carried directly in the responses of these filters, as evidenced by the fact that intervening bars have no effect on thresholds. A subsequent stage of processing is required to extract the position information. The experiments reported here indicate that an important property of this length gauge is its ability to choose the best spatial filter.

## **ACKNOWLEDGMENT**

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### Figure Captions

- Fig. 1 Three of the stimulus configurations used.
- Fig. 2 Fourier transforms of the "no parallels" and "four parallels" stimuli. The Fourier Transform of the "no parallels" stimulus was shifted vertically for clarity.
- Fig. 3 Separation discrimination thresholds for a pair of lines embedded in an array of four parallel lines at four exposure durations: 102 ms, 255 ms, 510 ms, and response-terminated. Also shown are data obtained with no parallels. Data are shown for three observers.
- Fig. 4 Diffusion screen calibration. The contrast threshold ratios were calculated by dividing the contrast thresholds obtained without the diffusion screen by the contrast thresholds obtained with the diffusion screen in place. Data are shown for two observers.
- Fig. 5 Effects of the diffusion screen on separation discrimination thresholds measured with four parallel bars and with no parallel bars. The threshold elevation ratio was obtained by dividing the threshold obtained with the screen present by the threshold *for the same stimulus condition* obtained without the diffusion screen. Thus, this ratio indicates the effect of the diffusion screen only. Data are shown for two observers.
- Fig. 6 Effects of parallel lines on separation discrimination thresholds. Data are shown for

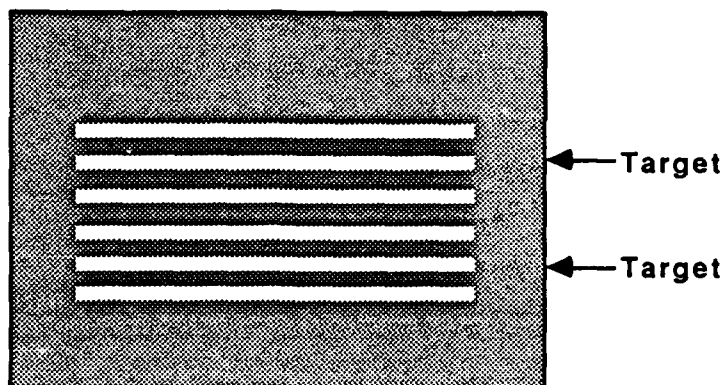
two observers and two exposure durations. "Outside parallels" is the stimulus condition shown in Fig. 1b. "Inside parallels" is the stimulus condition shown in Fig. 1c. "No parallels" is the standard two-line separation discrimination stimulus.

Fig. 7      Separation discrimination thresholds obtained under monocular and binocular viewing conditions for the four-parallels condition (as shown in Fig. 1a), for the outside-parallels condition (as shown in Fig. 1b), and for the no-parallels condition. Data are shown for two observers.

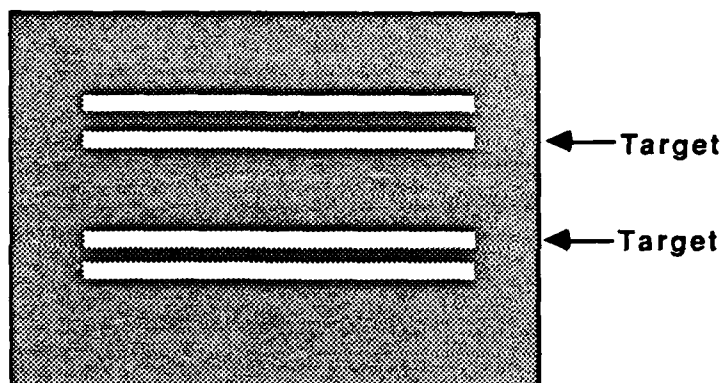
Fig. 8      Effect of diffusion screen on separation discrimination thresholds obtained with outside parallels (Fig. 1b) or inside parallels (Fig. 1c). Also shown for comparison are the data obtained with four parallels and with no parallels from Fig. 5. Data are shown for two observers.

Fig. 9      Separation discrimination thresholds for the four-parallels condition measured as a function of the average distance between each parallel and the nearest target.

a) Targets Embedded in  
Four Parallel Bars



b) Targets with Parallel Bars  
Outside



c) Targets with Parallel Bars  
Inside

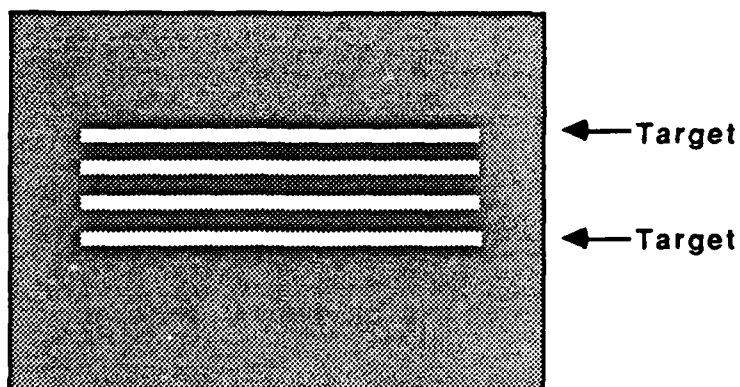


FIGURE 2

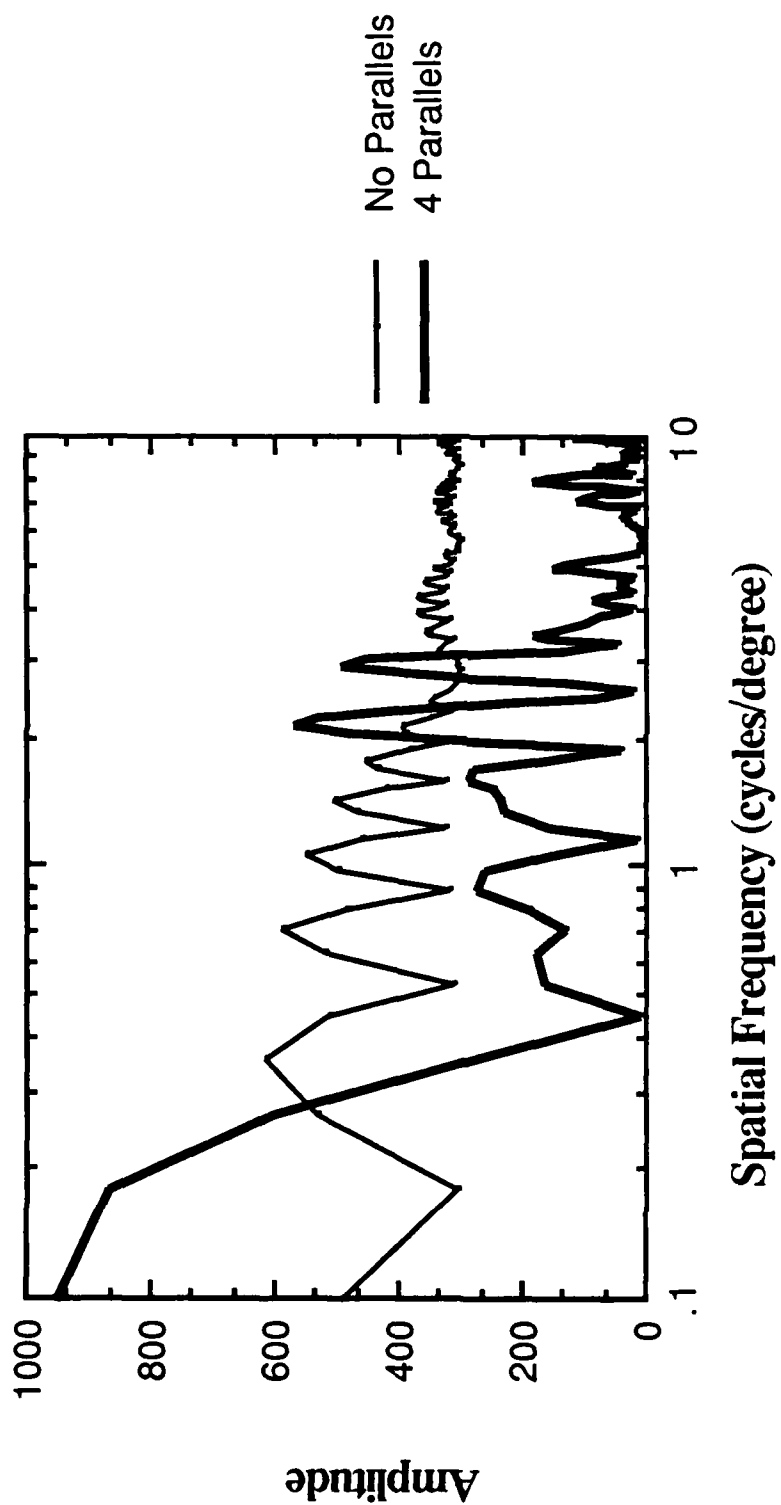


FIGURE 3

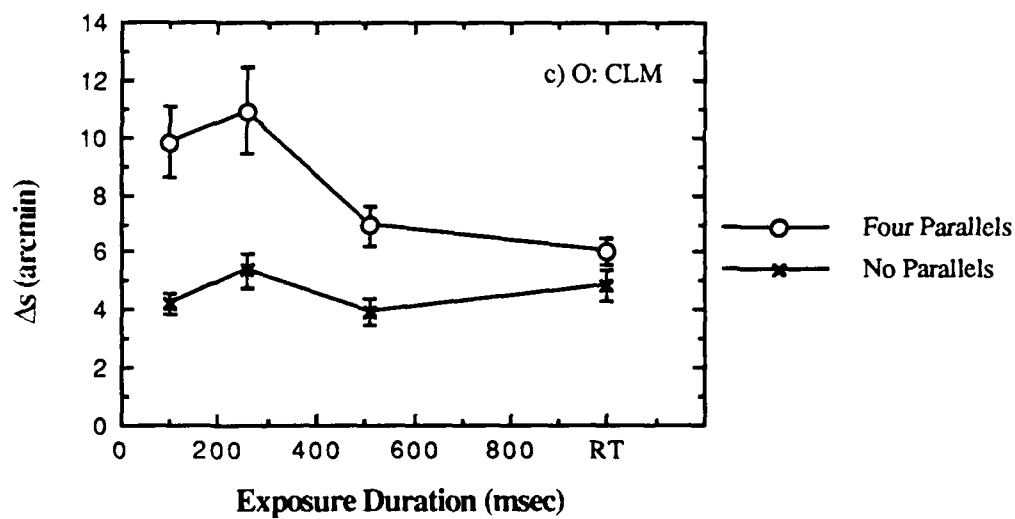
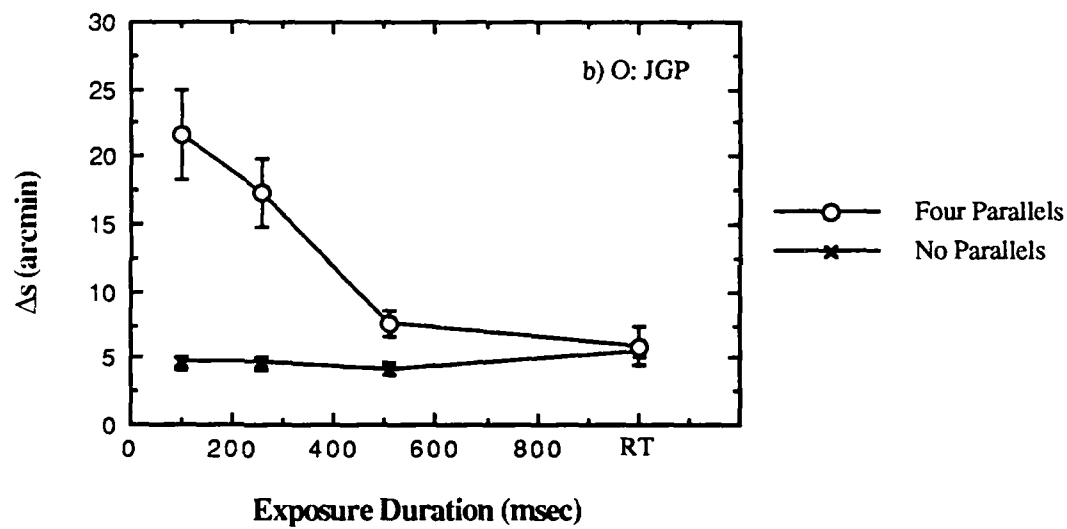
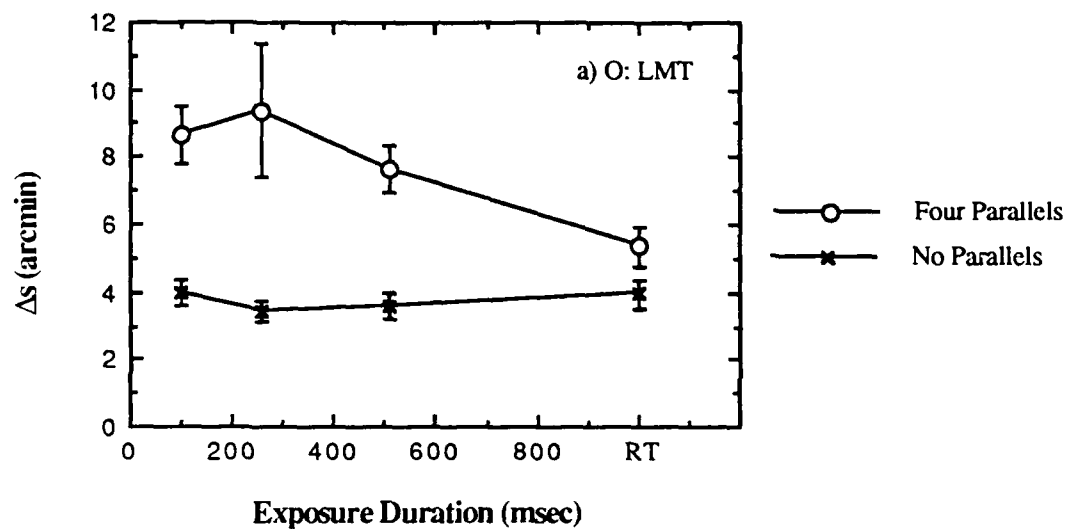


FIGURE 4

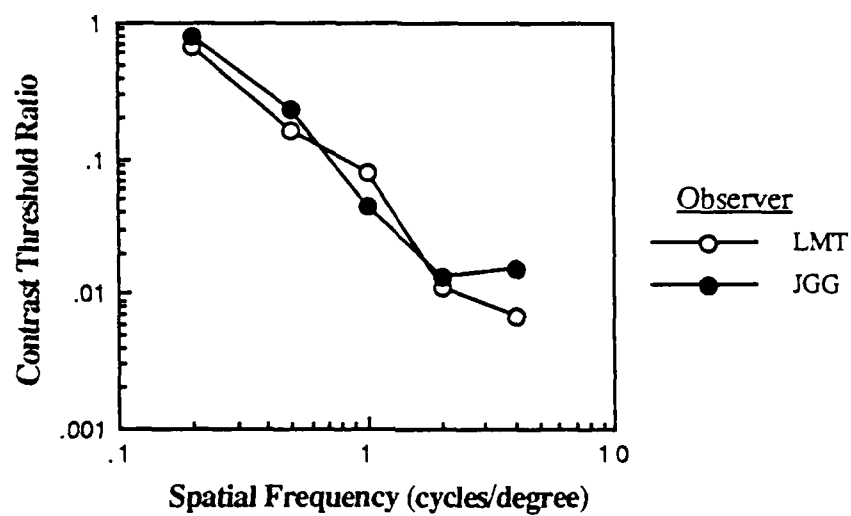
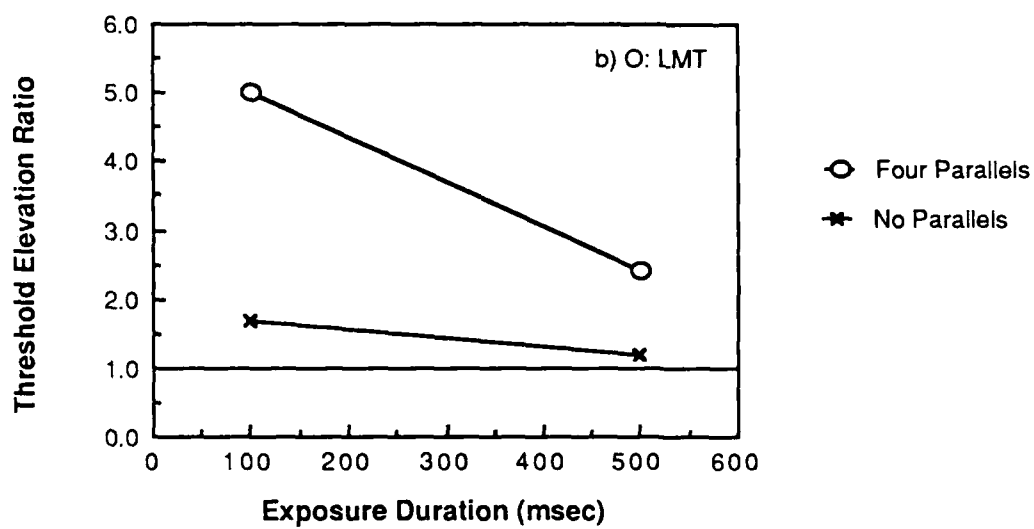
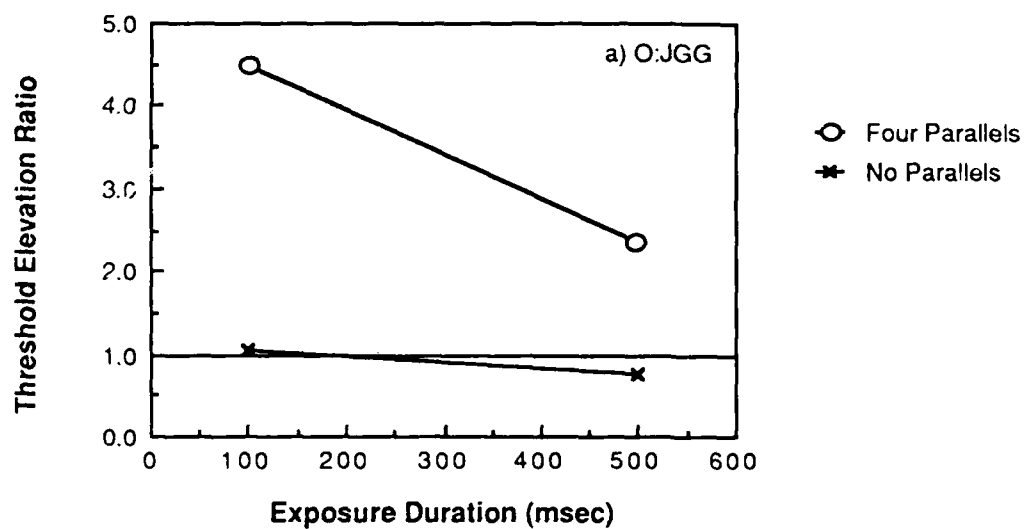


FIGURE 5



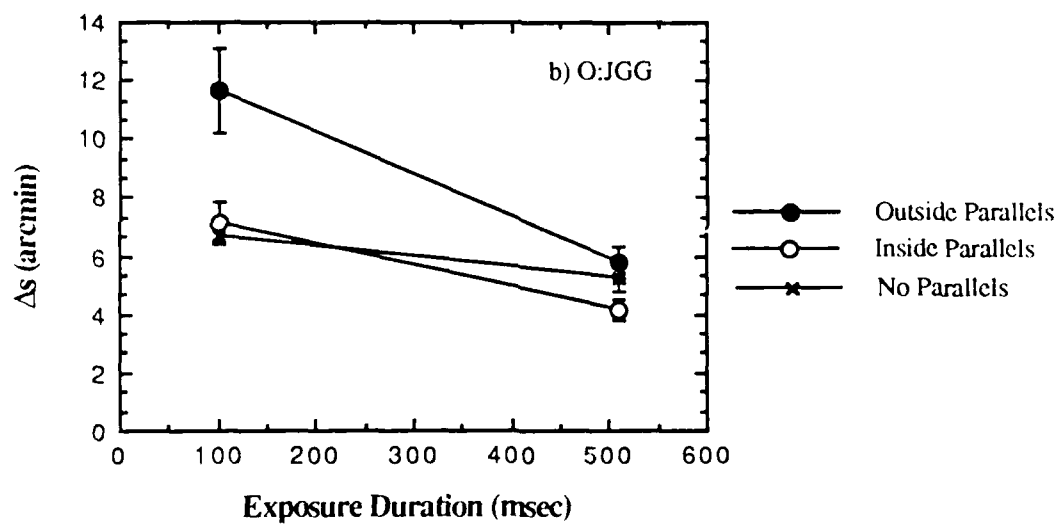
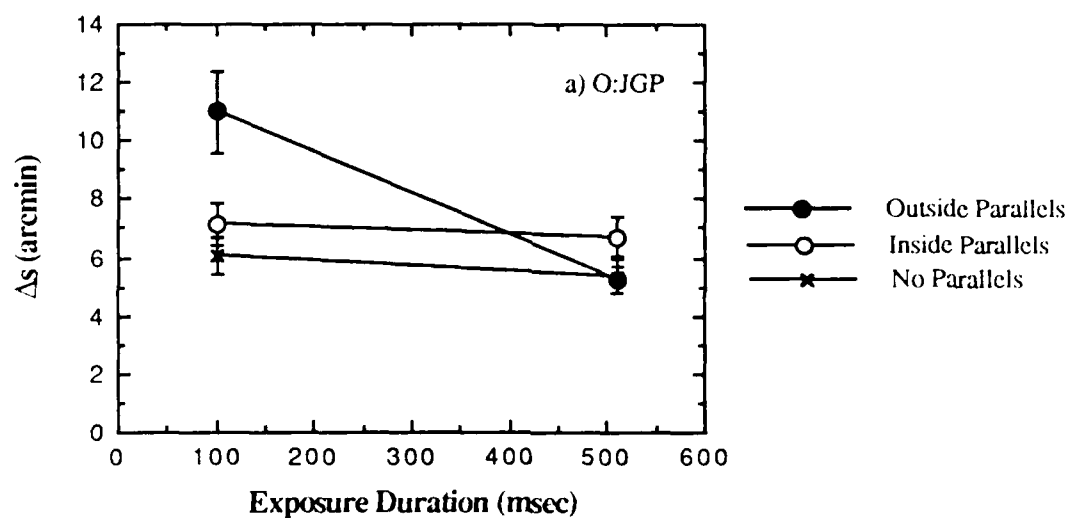


FIGURE 7

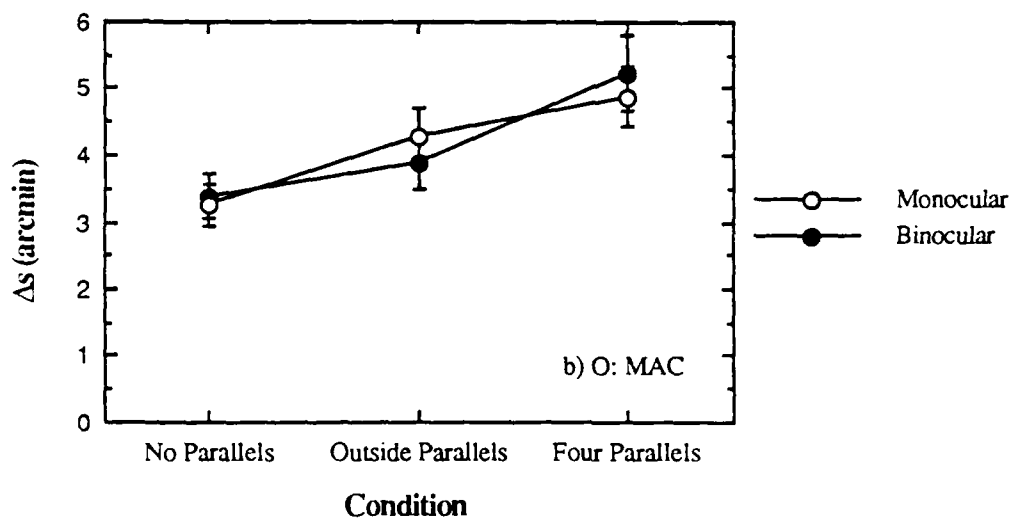
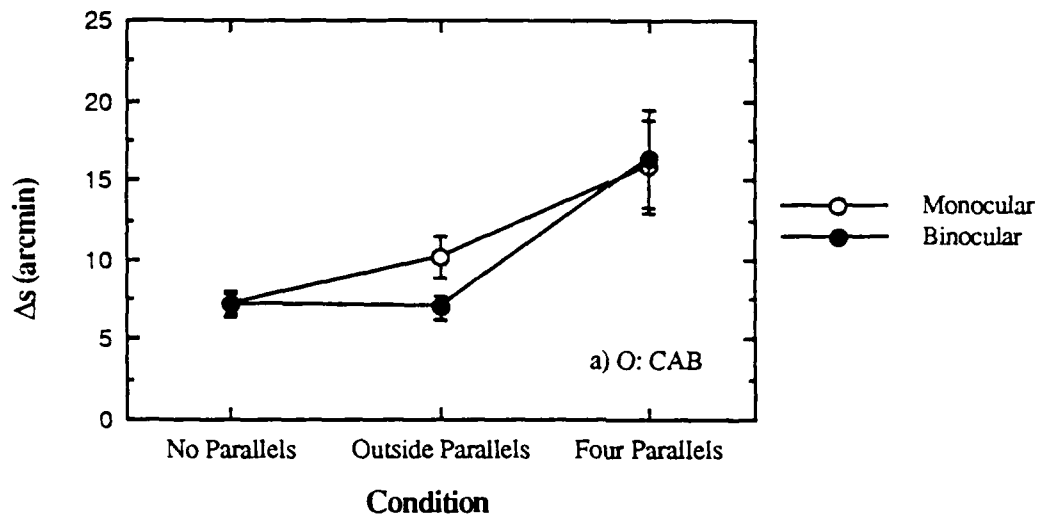
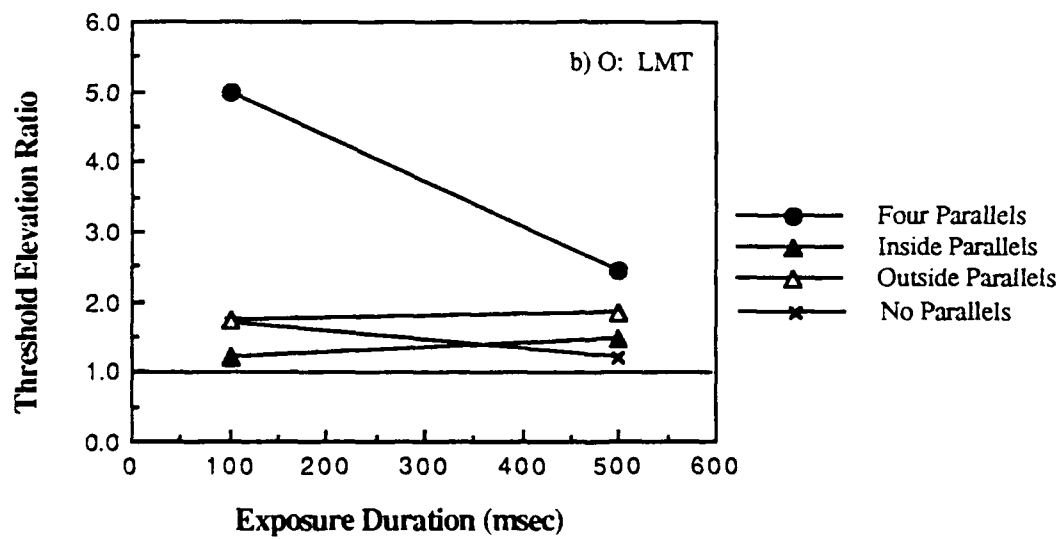
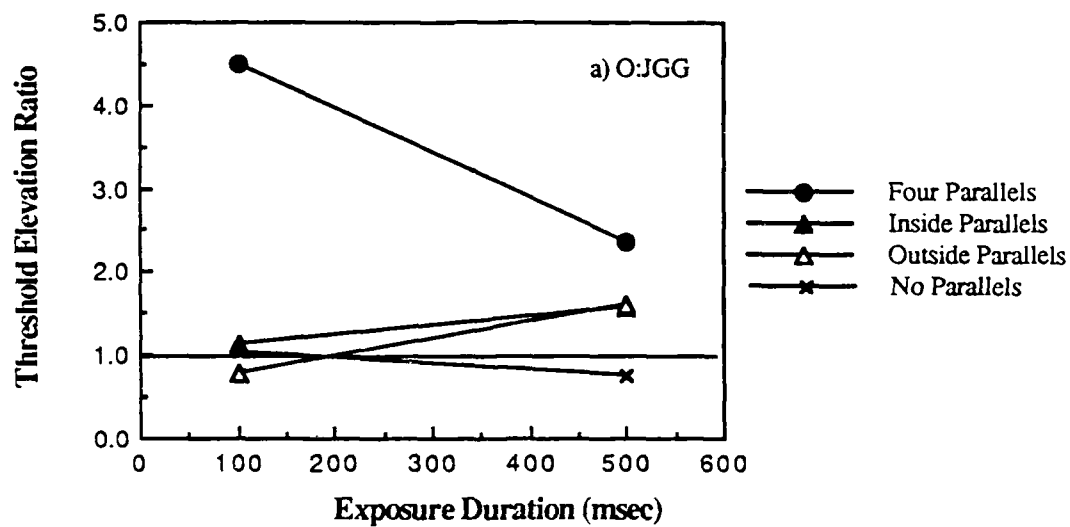
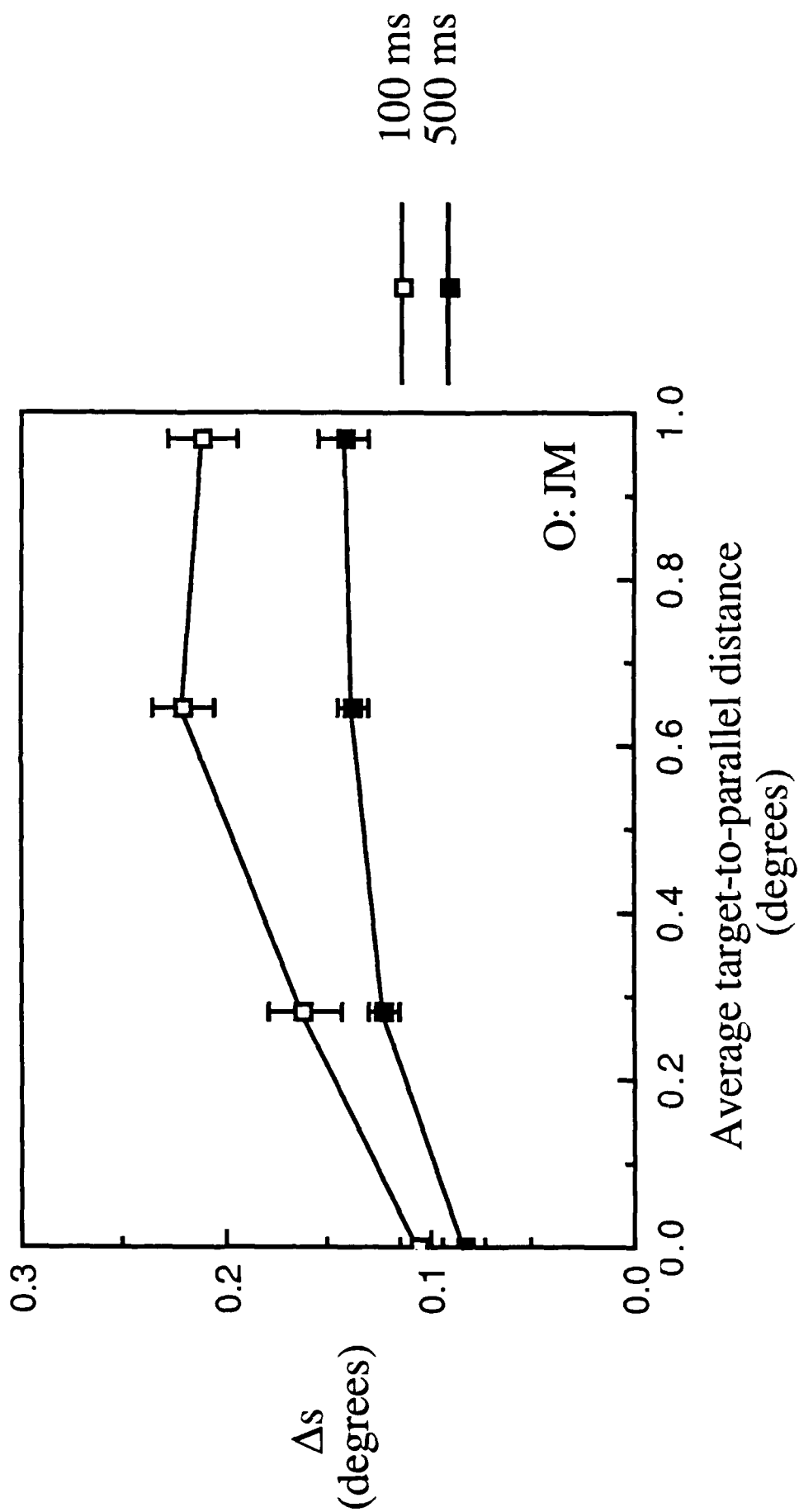


FIGURE 8





## Appendix C

### SPATIAL INTERACTIONS IN RAPID PATTERN DISCRIMINATION

To be submitted to *Spatial Vision*

## **Spatial interactions in rapid pattern discrimination**

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### **Abstract**

We measured reaction times (RTs) for identification of a target among distracters under stabilized image conditions in which the positions of the target and the distracters were constant within a single experimental session. Under these conditions, the observer need not search for the target because its position is known. We nevertheless found that the presence of even a single distracter could elevate RTs. The magnitude of this effect depended on the distance of the distracter from the target and, for some observers, the distance of the distracter from the fovea. When we added not one but six background elements in a ring around the target, RT increased even more. If, apart from these neighboring distracters, the target was surrounded by more distracters located beyond the nearest neighbors, RT was, in general, not increased further. These findings suggest that the increase in RT is caused by spatially lateral interactions between the target and neighboring distracters.

## Introduction

Reaction time procedures have been widely used to study the detectability of a target element in a display of nontarget elements. Specifically, experiments often measure RT as a function of the number of elements in the field, under the assumption that if RT increases with increasing number of elements, then the observer has engaged in a serial search, whereas if there is no such increase, then the elements have been processed in parallel (Treisman and Gelade, 1980; Bergen and Julesz, 1983; Pashler, 1987; Wolfe et al. 1988). This interpretation is supported by the finding that target detectability improves substantially if the observer knows in advance the location of the target, suggesting that the observer is able to direct his attention and process information from this location selectively (Engel, 1971; Eriksen and Hoffman, 1972; Posner, 1980; Kröse and Julesz, 1988).

Complicating this interpretation, however, is the finding that even if the target is presented at a fixed position, so that no "search" is necessary, the addition of more background elements can influence target detectability (Eriksen and Eriksen, 1974). Eriksen and Eriksen (1974) measured RT's for the identification of a target letter (always presented 0.5° above the fixation point) which was flanked by noise letters (3 left, 3 right) and found RT's elevated by the presence of the noise letters. More specifically, they found effects of target-noise similarity and of the between-letter spacing, for spacings up to about 0.5°. Whatever mechanism orients attention to the expected location of the target is apparently not able to ignore completely the activity at the nontarget locations. The experiments reported here examine the effects of such distractors with a peripherally located target. Our specific aim was to get a sense of the magnitude and extent of these distracter effects for a nonfoveal target, as compared to the results reported in the literature for a foveal target, looking in particular at the effect of the spacing between the target and the distracter and the effect of the retinal position of the distractor.

Bouma (1970) previously studied lateral interactions in the identification of a peripherally presented letter (between 1.5° and 10° eccentricity). His results show that the size of the area within which noise letters (1 left, 1 right) interact is approximately equal to 0.5 times the eccentricity at which the target is presented. However, in his experiments there was uncertainty about the target position; the target could occur either to the right or to the left of the fixation point. Because the observer could not attend to a single retinal location, the data from his experiments may exaggerate the magnitude of the interactions.

In our experiments, the target was always presented at a fixed location (3° above the fovea). Image stabilization was used to ensure consistent target placement without requiring the observer to foveate a fixation mark. This is important because deliberate foveation requires attention, and we wanted the observer to attend to the target location, not the fovea. This technique is also preferable, for our purposes, to the use of a visual cue with possible locations, because the cue itself draws attention, and we wished to determine the extent to which the observer could direct his attention without a visual trigger, as he must do if he is searching for a target.

## Methods

Stimuli were presented on a Macintosh Plus computer, which also served to measure RT's and percentage of errors. The stimuli were stabilized on the retina by an SRI Dual-Purkinje Eyetracker, Generation V, with stimulus deflector (Crane and Steele, 1985; Crane and Clark, 1978). All experiments were conducted with stabilized images.

The target and distracter elements were either *us* or *ns*, 0.47° in height and 0.30° in width. They were white (equal to the luminance of the background) and were presented on dark disks. Each

disk subtended  $0.78^\circ$  of visual angle. See Figures 1, 3, and 6 for examples of the stimuli. The mean luminance of the background was approximately 40 ft.L., maintaining photopic conditions. The background subtended  $9.8 \times 18.8^\circ$  at the 50.5-cm viewing distance (measured from the second servo-driven mirror of the stimulus deflector, which is optically conjugate with the pupil).

The target was always presented in the same spatial position,  $3.1^\circ$  above the fovea on the vertical meridian. The stimuli came on abruptly and remained on until the observer responded. No fixation mark was needed during the experiments because the stimulus was stabilized on the retina. The target was present on every trial and the observer had to report, as rapidly as possible (while maintaining a constant low level of errors), whether he saw an *n* or a *u*. Depending on the experimental condition, one or more distracters could be presented simultaneously with the target. The number and positions of the distracters were constant during a single experimental session. The observer distinguished the target from the distracters only by its position. In the initial experiments, the distracters were all *us*; in subsequent experiments they were randomly *us* or *ns*.

A block consisted of 110 trials. The RT's of the first 10 trials of each block were not used in calculating the average, but served as a brief practice. Extensive practice was done before collecting any of the data included in the main body of this report. The results of the practice sessions are shown in Appendix A.

Before each block of trials, a fixation point was presented in the center of the display. The observer adjusted the offset of the stimulus deflector to make this fixation point coincident with his center of gaze (and, we assume, coincident with the center of his fovea). The fixation point disappeared prior to the first trial and did not return until the end of the last trial in the block, when the observer confirmed that it still coincided with his center of gaze. (It always did.)

Care was taken to randomize the order in which data were collected for the different conditions, in case there were residual learning effects. In addition, we measured RT for the *no-distracter* condition several times each day and used that as the baseline for that day's data. (Preliminary experiments showed that RT's fluctuate from day to day even after the initial learning period is over. See Appendix A.) Performance is expressed as the difference between the RT with distracter(s) and the average no-distracter RT for the day. Data were obtained from at least three 110-trial blocks for each condition, unless indicated otherwise.

### Surrounding the Target with Distracters

In these experiments the target element was surrounded by background elements as shown in Figure 1. Two conditions were used. There were either six background elements arranged in a hexagonal "one-ring" configuration around the target, as shown in Figure 1(a), or eighteen background elements arranged in a "two-ring" configuration, as shown in Figure 1(b). In this experiment, the background elements were all *us* (although the target could be a *u* or an *n*). Reaction times for identification of the target, whose position was always known, were measured and compared to the no-distracter condition. The spacing of the target-distracter array was a parameter of the experiment. With a hexagonal arrangement, the distance between any two adjacent elements is constant for a given spacing; thus, for example, a spacing of  $1.2^\circ$  means that the distance between any element (target or distracter) and its nearest neighbor was  $1.2^\circ$ .

-----insert Figure 1-----

The number of background elements (6 or 18) and the spacing were kept constant during a block

(110 trials). RT's for the "one-ring" condition were measured for spacings ranging from 1.2° to 4.8°. RT's for the "two-ring" condition were measured for spacings ranging from 1.2° to 2.4° (1.2° to 3.1° degrees for Observer B) because of limitations imposed by the display size. We also measured RT for the identification of the target element presented alone (the no-distracter condition) for comparison.

-----insert Figure 2-----

The data from these experiments are shown in Figure 2. For both observers, the presence of the background elements elevates RT. The magnitude of that RT elevation decreases with increasing spacing, but is still significant at spacings of 2°-3°. Interestingly, the data for the two-ring condition are very similar to the data for the one-ring condition. Adding background elements outside the first ring did not further elevate RT. Thus, it is the nearest neighbors that delay identification of the target element. To study the extent to which these interactions depend on the number and position of the background elements, we conducted the following experiments.

### **A Single Distracter**

Instead of surrounding the target with background elements, we added a single background element at various positions relative to the target. The background element was the same throughout each experiment: a white u on a black disk. The six distracter positions used in the experiment are shown in Figure 3, where a distracter is placed at Position 1 as an example. The position of the distracter was constant during a block of trials.

-----insert Figure 3-----

We measured RT with and without a background element at a fixed spacing of  $1.2^\circ$ . We found that the data were symmetric across the vertical axis: RT's for background elements to the left of the target were, in general, not significantly different from RT's for background elements to the right of the target. Therefore, the data were averaged across the left and right positions. Positions 1 and 2 are above the target and have a larger eccentricity than the target, Positions 0 and 3 are beside the target and have a similar eccentricity, and Positions 4 and 5 are below the target and have a smaller eccentricity.

The change in RT ( $\Delta RT$ ) caused by the presence of the background element is shown in Figure 4 by the open symbols. For all distracter positions,  $\Delta RT$  is negative. Apparently, the effect of the second element was slightly facilitory. The Observer indicated that she was not "identifying the target element" but instead was making a same-different judgment. If her report is accurate, then the same-different judgment must be more rapid than identification of the target element.

-----insert Figure 4-----

To avoid responses based on same-different judgments, we let the background element be either a u or an n, chosen randomly from trial to trial. Results of this experiment are shown by the filled symbols in Figure 4. Under these experimental conditions, RT's are significantly elevated by the presence of the second element.

### *Target-Distracter Spacing*

To get a more detailed picture of the effect of a single distracter on RT, we studied the change in RT (relative to the no-distracter condition) as a function of position (as shown in Figure 3) for a range of spacings. Results for three additional observers are given in Figure 5. The data are averaged across corresponding left and right positions as in Figure 4.

-----Insert Figure 5-----

There are large and consistent intersubject variations in the effect of a single distracter. Observer C is less sensitive to a distracter than are Observers D and E. A two-way analysis of variance (ANOVA) applied to the data of Observer C shows that the effect of position is not significant [ $F(2,75)=1.25$ ,  $p>.25$ ] and that the effect of spacing is also not significant [ $F(4,75)=1.52$ ,  $.10<p\leq.25$ ]. However, for Observer D, both the effects of position [ $F(2,105)=3.96$ ,  $.01<p\leq.025$ ] and spacing [ $F(4,105)=4.37$ ,  $.0001<p\leq.005$ ] are significant. For Observer E, the effects of spacing and position are even more prominent [effect of position,  $F(2,75)=17.5$ ,  $p\leq.0001$ ; effect of spacing,  $F(4,75)=8.28$ ,  $p\leq.0001$ ].

Data for Observer E also show an effect of the position of the distracter relative to the fovea. A distracter placed below the target (i.e., nearer the fovea) has a larger effect than does one next to or above the target. This pattern suggested the following experiment in which we examined the effect of the retinal position of the distracter.

### *Retinal Position of Distracter*

Although the background elements at Positions 4 and 5 (Figure 3) come close to the fovea for spacings of  $2^\circ$  or  $3^\circ$ , they never come closer than  $1.5^\circ$  from the center of the fovea. To determine the effects of the retinal positions of the distracters more systematically, we used a different set of positions. Spacing between the target and distracter was fixed at  $3.1^\circ$ . Distracter position was varied from  $\theta = 0^\circ$ , distracter to the right of the target, to  $\theta = -180^\circ$ , distracter to the left of target, in seven equally spaced steps along an equidistant arc below the target. At  $\theta = -90^\circ$  the distracter is presented at the fovea. Results are shown in Figure 6. In addition to Observers C and D, who participated in the previous experiment, two other observers participated in this experiment.

-----insert Figure 6-----

For Observers A and F, a single background element can have a large effect on RTs. The analysis of variance on the effect of position shows that this effect is significant for Observer A [ $F(6,14)=10.1$ ,  $.0001 < p \leq .005$ ] and Observer F [ $F(6,21)=2.97$ ,  $.025 < p \leq .05$ ]. An increase in RT also occurred for Observer D, but the effect is relatively small and not significant: the effect of position is [ $F(6,28)=1.56$ ,  $p > .25$ ]. Observer C is very good at ignoring the background element. No significant increase is observed if the background element is presented on the fovea [effect of position,  $F(6,21)=1.49$ ,  $10 < p < .25$ ]. The lack of effect found for Observers C and D was not caused by long RT's in the no-distracter condition. Observer C, who showed the least effect of the single distracter, had the shortest RT's of all observers (mean no-distracter RT of 435 ms).

To compare these results with the data obtained with one or two rings of distractors, we redid

those experiments with Observers C and D and also did them with Observer E.

### **Surrounding the Target with Mixed Background Elements**

In the first experiment of our study, we surrounded the target with either one ring (6 elements) or two rings (18 elements) of a single type (always a **u**). However, in the single-distracter experiments we found that the choice of background conditions (single **u** or mixed **us** and **ns**) influenced performance. Therefore, we repeated the ring experiments, using a background formed from a mixture of **us** and **ns**. The results are shown in Figure 7, where we plot the increase in RT as a function of spacing for the one- and two-ring conditions. As a comparison, we also show the maximum RT elevation obtained on the one-distracter condition (as given in Figure 5).

-----insert Figure 7-----

Observer C continues to be relatively insensitive to distracters even when the target is surrounded by them. However for Observer D, RT is elevated by the rings, even at large spacings. The data of Observer E are very similar to the  $\Delta RT$  vs spacing curves from Observers A and B in the first experiment. In general, there appears to be a basic pattern of results, but there are also marked deviations from that pattern for some observers.

A two-way ANOVA (number of rings x spacing) applied to the data for spacings less than  $2.4^\circ$  shows that the effect of adding the second ring is not significant for Observers E [ $F(1,12)=.43$ ,  $p>.25$ ] and C [ $F(1,12)=1.4$ ,  $p>.25$ ] but is significant for Observer D [ $F(1,18)=19.99$ ,  $.0001<p\leq.005$ ]. The effect of adding six background elements instead of one is small for

Observer C, but large for the other two observers. A two-way ANOVA (number of distracters x spacing), again applied to the data for spacings less than  $2.4^\circ$ , shows for Observer C [ $F(1,35)=0.516, p>.25$ ], Observer D [ $F(1,50)=19.2, p>.0001$ ], and for Observer E [ $F(1,35)=10.9, .0001 < p \leq .005$ ]. The effect of spacing (a two-way ANOVA, condition x spacing) is significant for all three observers: Observer C [ $F(2,27)=2.96, .05 < p \leq .10$ ], Observer D [ $F(2,39)=7.25, .0001 < p \leq .005$ ] and Observer E [ $F(2,27)=20.0, p \leq .001$ ].

The results of this experiment are comparable with the results from our first experiment. Adding background elements farther away than the nearest neighbor does not usually affect RT. However, if the number of nearest neighbors is increased from one to six, RT's generally increase. We averaged the  $\Delta RT$ 's of all observers, including the data of Observers A and B from Experiment 1 for the one-ring and two-ring conditions, and the maximum RTs for the single distracter condition for Observers C, D, and E. These composite curves are given in Figure 8.

-----insert Figure 8-----

In general, there are strong interactions when the distracters are within  $3^\circ$  of the target, which is itself located  $3.1^\circ$  above the fovea. The fact that the addition of 12 more background elements causes no additional impairment shows that these interactions are restricted to the nearest neighbors. The difference between the one-distracter and the one-ring data indicates that these lateral interactions depend on the number of distracters present.

## Discussion

Even though the target was presented at a fixed retinal position during the entire experiment, so that the observer was certain of its location (both relative to the display edges and absolutely on his retina), there was still a significant effect of the distracters. This effect appears to depend, at least in some observers, on the spacing between the distracters and the target, and on the retinal position of the distracter relative to the fovea.

Results presented in Figure 5 show that a single background element has at most a small effect if it is presented at a larger eccentricity than the target, even if it is relatively close to the target ( $1.2^\circ$  in this case). However, a single background element presented at the same (or smaller) eccentricity than the target can have a significant effect, the magnitude of which depends on the spacing between the target and the distracters. When this single background element is presented on the fovea, there can be a large increase in RT.

Lateral interactions that are dependent on the spacing between the distracters and the target have been reported in two studies in which the exact target location was not known to the observer. In the Bouma (1970) study mentioned above, the target could occur in either of two widely separated locations, so that the observer could not attend to the target location prior to stimulus presentation. Sagi and Julesz (1985) also report spatial interactions of the type seen here, in their study comparing the identifiability of a single target to the discriminability of two targets. They found that the second target masked the first when the two were separated by less than  $2^\circ$  for a target eccentricity of  $4^\circ$ , and when they were separated by less than  $6^\circ$  for a target eccentricity of  $12^\circ$ . In their task, the observer had to attend to both targets and the position of the targets varied randomly from trial to trial. In our experiments, the observer knew the target location exactly. Nevertheless, the spatial extent of the interactions we found is not smaller than they found. Thus, knowing the target location in advance does not appear to diminish the extent of the effects.

Lateral effects outside the classical receptive field (CRF) have also been found electrophysiologically. There is increasing evidence that for many visual neurons, stimuli presented outside the CRF strongly and selectively influence responses to stimuli presented within the CRF (for a review, see Allman et al., 1985). For example, a moving background strongly affects the direction and velocity tuning of many cells in the middle temporal area (Allman et al., 1985) and in Areas V1 and V2 (Allman et al., 1988) of the owl monkey. DeYoe et al. (1986) have reported analogous surround effects using static texture patterns in Area V1 and V2 of macaque monkeys. In their experiments, texture background often suppressed the response to a target within the CRF, sometimes in an orientation-specific manner. It is unknown whether these interactions are caused by intrinsic connections or by the many descending pathways (Maunsell and Van Essen, 1983) from higher cortical areas.

Such intrinsic connections within a cortical area might account for some of our data, but they do not readily explain the foveal effects we found, which vary profoundly among observers. The inhibition we observed in our experiments may be nothing else than an involuntary shift of attention, caused by the foveal stimulus. It has been shown (Kröse and Julesz, 1988) that an invalid cue presented prior to the stimulus may affect performance. Even distracters at a higher eccentricity than the target affect performance if these distracters are presented 40 ms before stimulus onset (Gathercole and Broadbent, 1987). By analogy to distracters that are presented before stimulus onset, it is possible that distracters presented *foveally* may affect the orienting of attention. They are responded to more rapidly, as shown in Appendix B.

We have shown that even in a nonsearch task, additional background elements can affect discrimination RT's and the magnitude of the effect depends on the positions of these background elements relative to the target and, for some observers, relative to the fovea. When the effects of the number of background elements in a search task are used as an argument for serial processing,

special attention has to be given to the positions of the target and background elements to distinguish lateral interactions from serial processing.

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## **Appendix A: Effect of Training**

During the experiments, a substantial learning effect was found. For this reason, all observers went through a training period in which practice trials of the no-distractor condition were done. The observers were shown their average RT and number of errors after every 110 trial session. Data on performance during this period were recorded for three observers. These data are plotted in Figure A-1 as the average RT for each day of testing. Data for the no-distractor condition obtained during the main experiments are also shown. Observer C started with the main experiments on Day 3 and had 11 practice runs (of 110 trials each). Observer E started on Day 3 after 17 practice runs, and Observer F started on Day 4 after 15 practice runs.

-----insert Figure A1-----

Figure A-1 also shown the magnitude of the day-to-day variations in RT. In this paper we expressed performance as the difference between the RT *with* distracter(s) and the RT *without* distracter to factor out some of this variability.

## **Appendix B: Effect of Eccentricity**

For eccentricities less than 20°, performance on a variety of visual threshold tasks varies approximately linearly with eccentricity (Weymouth, 1958; Anstis, 1974) when this performance is measured with visual acuity. How does performance depend on eccentricity if the task is above threshold, and RT's are measured? An increase in RT with increasing eccentricity was found by

Lefton and Haber (1974), using a same/different task with small characters on the horizontal axis. In our experiment the task was identification (not a same/different discrimination) and our elements were twice the size of those used by Lefton and Haber, so we decided to study the effect of eccentricity on RT ourselves, using both the horizontal and the vertical axes.

-----insert Figure A2-----

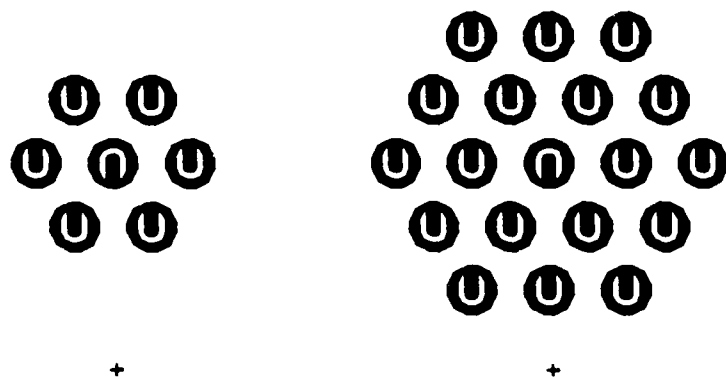
The results for two observers are given in Figure A-2. Both observers show an increase in RT with increasing eccentricity. For Observer B, this increase begins at small eccentricities and continues almost linearly whereas for Observer A, the RT's are essentially independent of eccentricity at small eccentricities, but increase sharply beyond about 4° eccentricity. For small eccentricities, we found no significant effect of radial anisotropy: the vertical and horizontal RT's were the same. In these experiments, RT for the most eccentric location in the upper visual field (6° vertical) was elevated because of its nearness to the edge of the display. This problem was avoided in the experiments reported in the body of this report by placing the fixation cross below the center of the display. For the most eccentric horizontal target positions, there was a difference between the left and the right (of the observer): target presentation to the right of the fixation point resulted in a lower RT than target presentation to the left of the fixation point. This agrees with the data of Perry et al. (1984) on the distribution of ganglion cell density across the retina: at a given retinal eccentricity, ganglion cell densities are several times greater along the nasal horizontal meridian than along the other three meridians.

### Figure Captions

- Figure 1      The target element ( $\cap$ ) surrounded by either one or two rings of distracters (U's). The small cross shows where the subject fixated (the cross was not present during the trials). Fixation accuracy was ensured by image stabilization.
- Figure 2      Elevations in RT's caused by surrounding the target by one or two rings of distracters, as shown in Fig. 1, for a range of spacings between the target and the distracters. Data are shown for two observers.
- Figure 3      Positions of distracter used in single-distracter experiments. In this example, the distracter is presented at Position 1. The target ( $\cap$ ) was always in the same location. The small cross, which was not visible during the trials, is the fixation point.
- Figure 4      Change in RT caused by the presence of a single distracter. Open symbols show the results obtained when the distracter was always a U. Filled circles show the results obtained when the target could be either a U or an  $\cap$ , varying randomly from trial to trial. The position names refer to the scheme presented in Fig. 3.
- Figure 5      Change in RT caused by the presence of a single distracter (which could be a U or an  $\cap$ ). Data are shown for three observers and a range of target-distracter spacings.

Distracter positions refer to the naming scheme shown in Fig. 3.

- Figure 6      Change in RT caused by the presence of a single distracter presented at a constant distance of  $3.1^\circ$  from the target at various angles. At  $-90^\circ$  orientation, the distracter was on the observer's fovea. Data are shown for four observers.
- Figure 7      Change in RT caused by the addition of a single distracter or one or two rings of distracters. For the single-distracter condition, the  $\Delta RT$  used is the maximum of the values shown in Fig. 5 for each observer and spacing.
- Figure 8      Averages of the data shown in Figs. 2 and 7, showing the general pattern of results obtained.



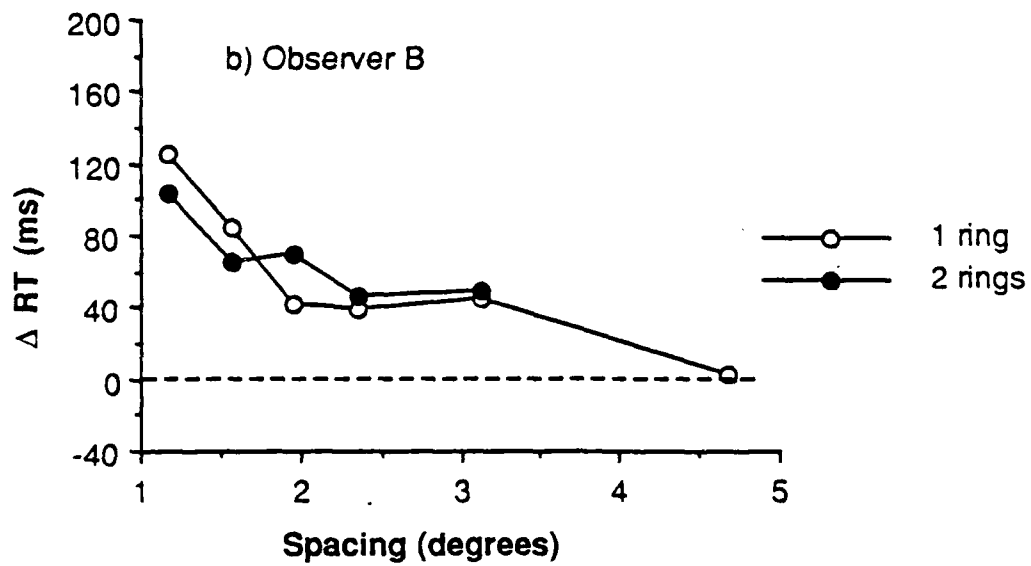
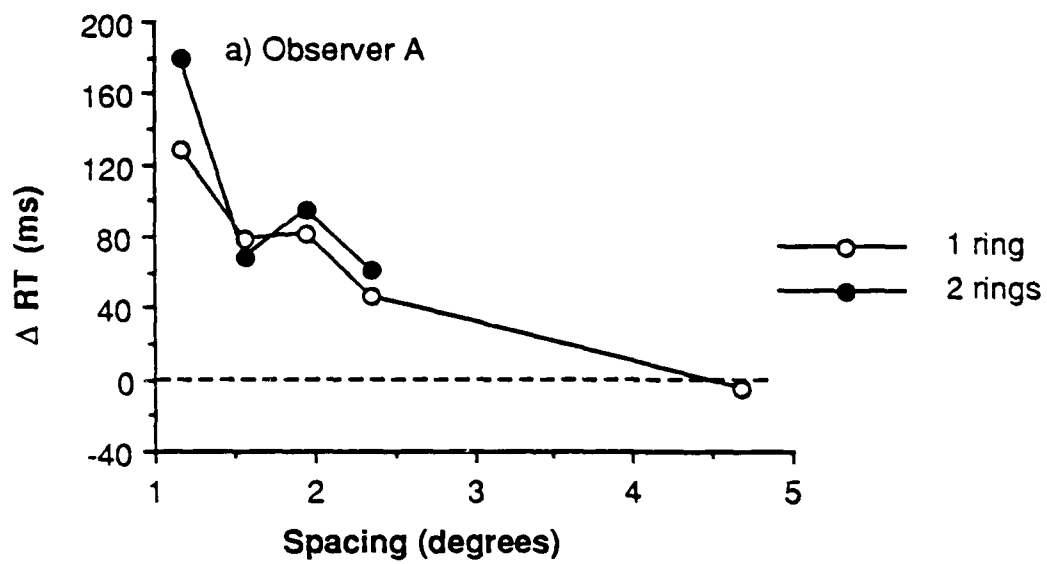
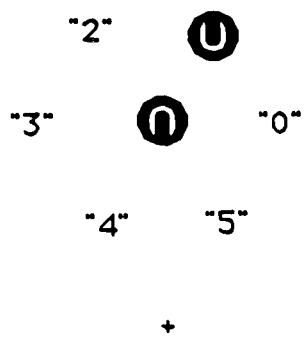
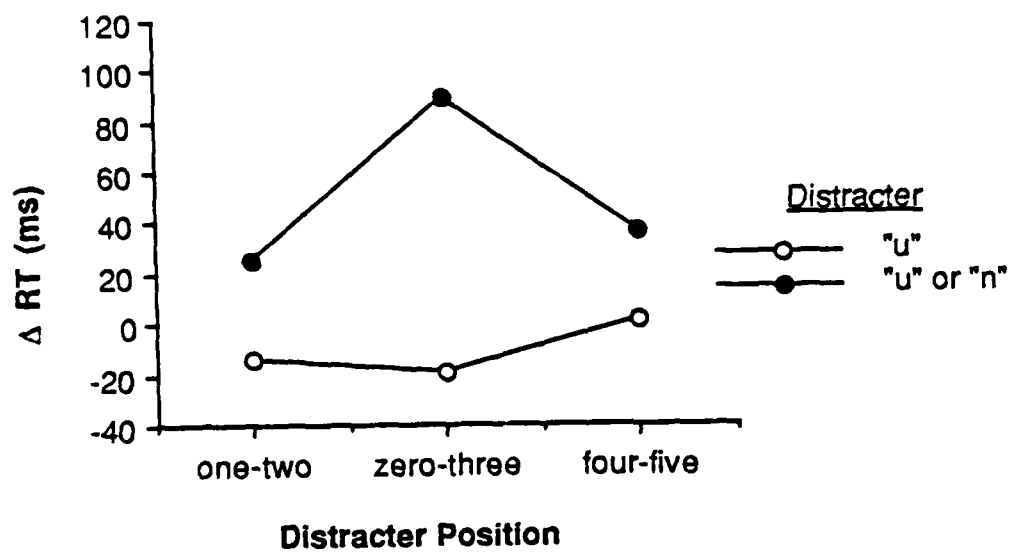


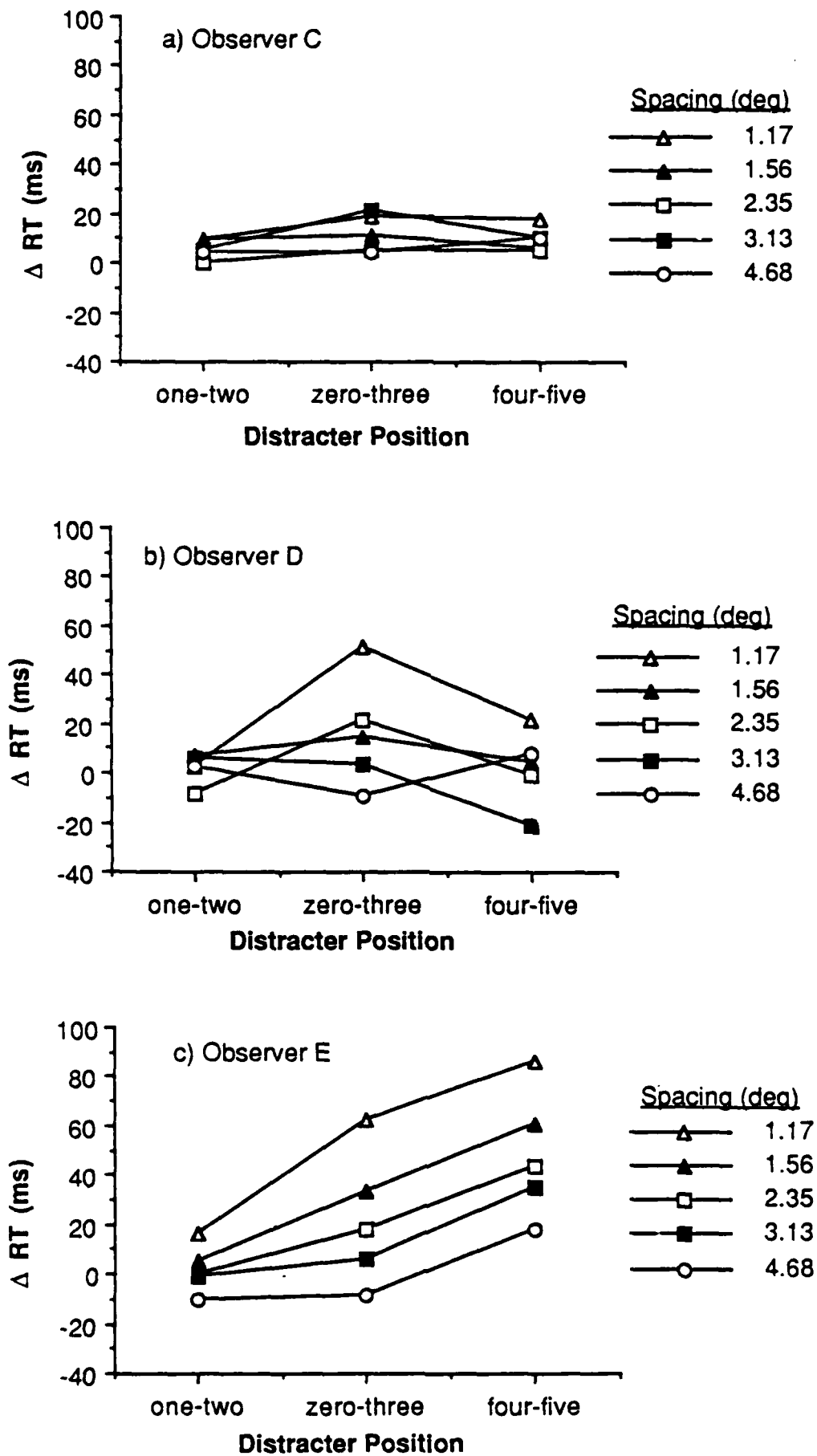
FIGURE 2

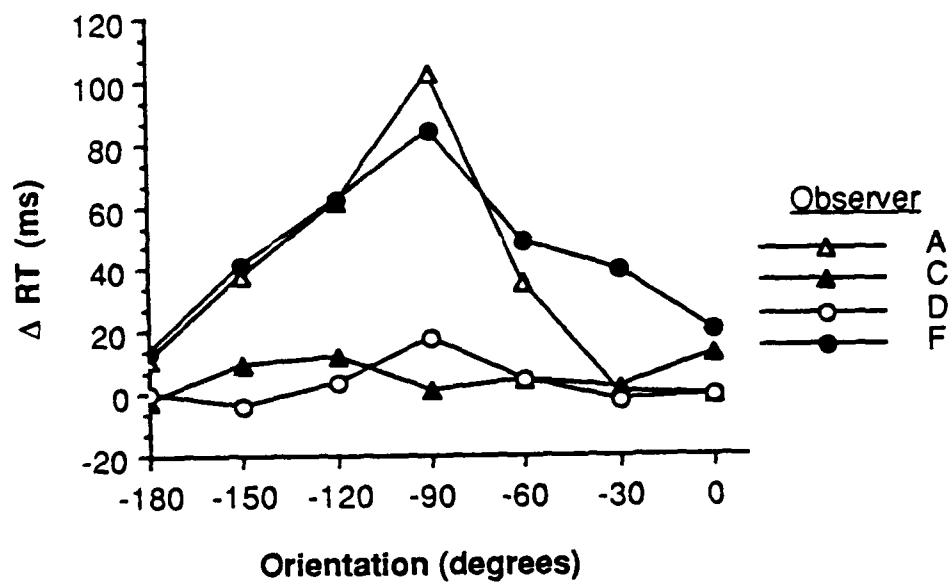


C-25

FIGURE 3







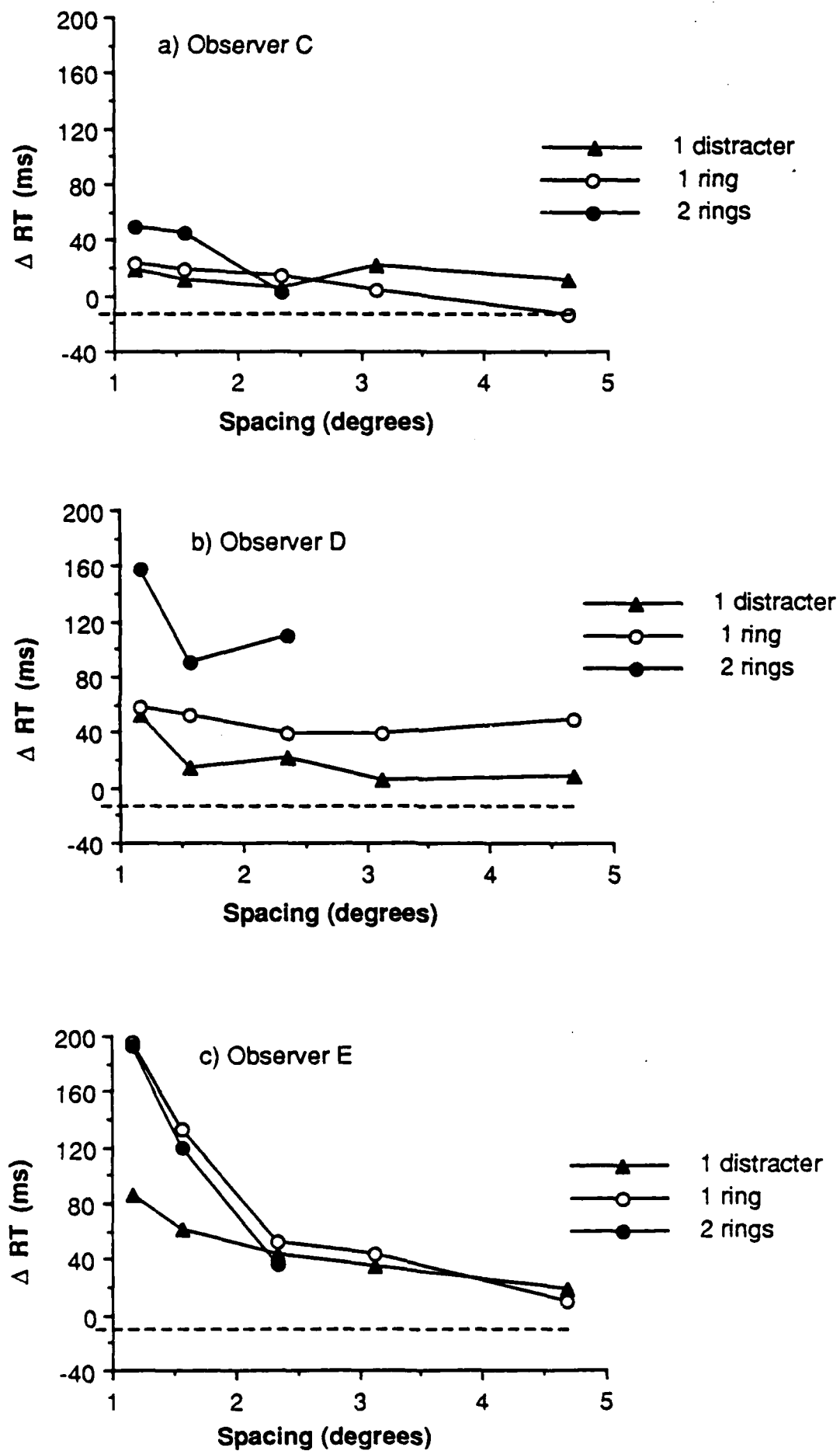
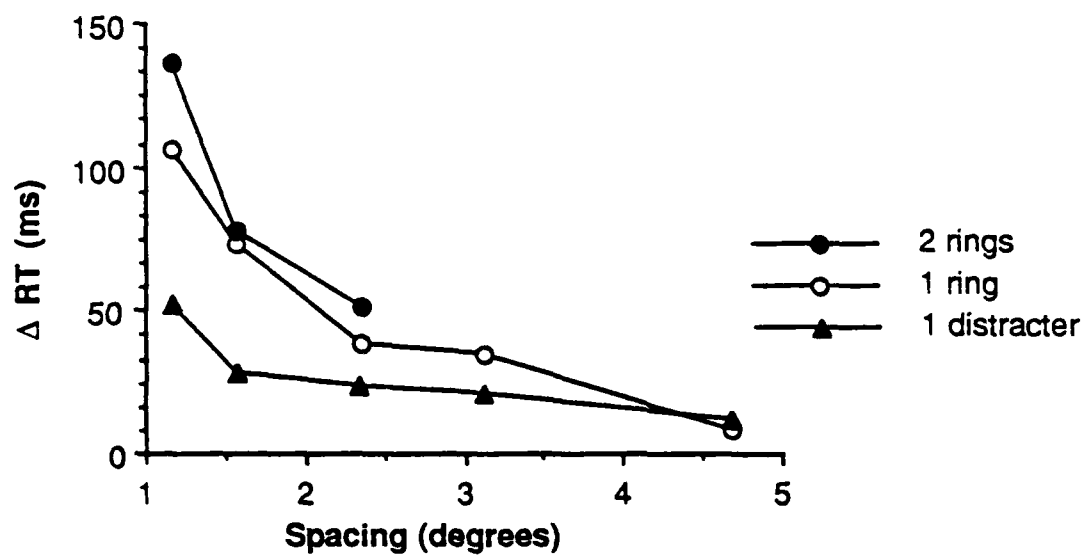
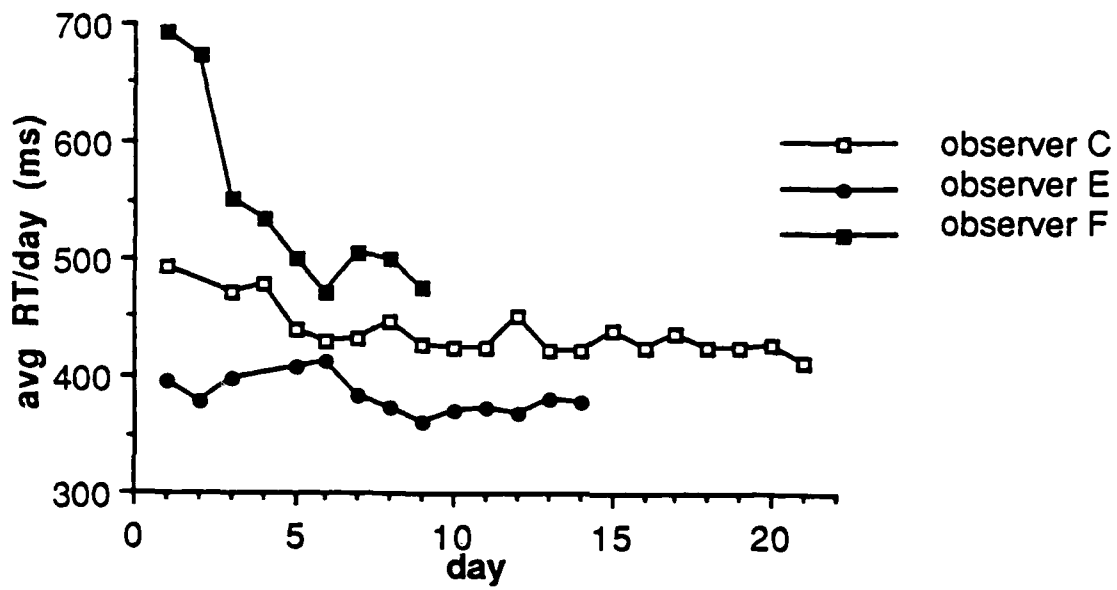
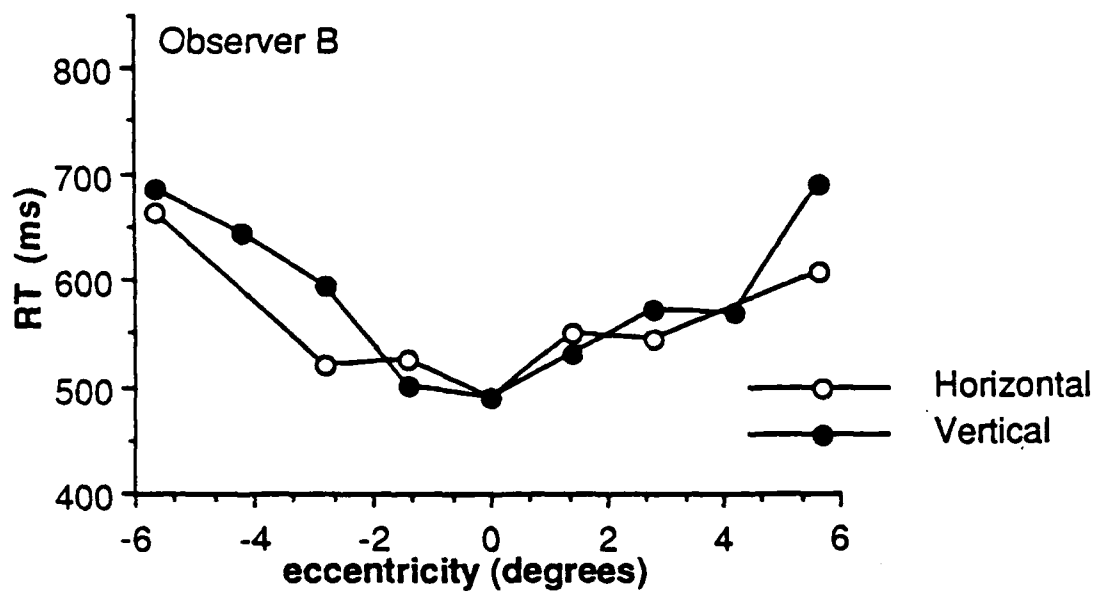
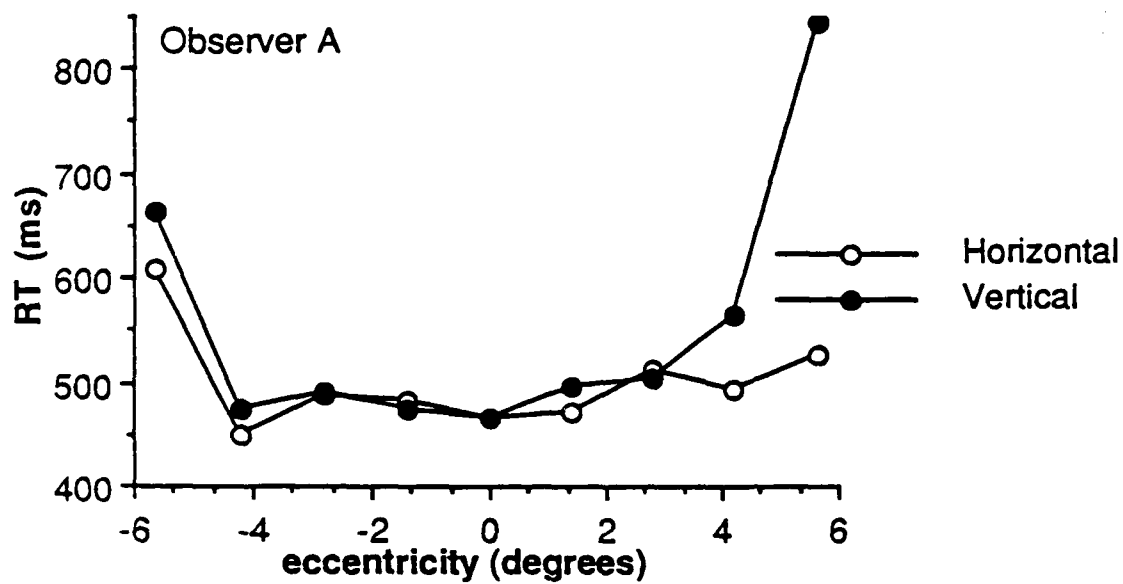


FIGURE 7







## **Appendix D**

### **PERCEIVED SPATIAL FREQUENCY SHIFT: ORIGIN AND IMPLICATIONS**

Draft submitted to *Vision Research*--now being revised.

# **Perceived Spatial Frequency Shift: Origin and Implications**

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**Keywords:** Pattern adaptation, perceived spatial frequency shift, spatial frequency discrimination, contrast detection.

**Abstract** – The effect of pattern adaptation on perceived spatial frequency is examined to determine whether it is tied to the retinal spatial frequencies of the test and adapting gratings or to their object spatial frequencies. The data show clearly that the perceived spatial frequency shift (PSFS) is tied to the retinal spatial frequencies. In a control experiment, we confirm a previous finding that contrast-threshold elevation following pattern adaptation is also tied to the retinal, not object, spatial frequencies of the adapting and test gratings (Blakemore *et al.*, 1972). Together, these findings support the hypothesis that both adaptation phenomenon result from a single process.

Using a simple model for the relationship between perceived spatial frequency and frequency discrimination, we show that the PSFS implies that frequency discrimination thresholds should also be altered by pattern adaptation. We conduct experiments to test this implication and find it supported by our data. However, comparing these experimental and theoretical results to previous findings indicates some contradictions.

## INTRODUCTION

Recent research in spatial vision has been dominated by the idea that the early stages of spatial vision can accurately be modeled as a set of filters that are selectively sensitive to a limited range of spatial frequencies (DeValois and DeValois, 1980; Kelly and Burbeck, 1984). The original spatial-frequency-channels concept has been modified to reflect the spatially localized nature of early spatial processing (Wilson and Bergen, 1979), but the basic concept of multiple spatial-frequency selective mechanisms remains a dominant theme. One cornerstone of this theory is the fact that prolonged viewing of a high-contrast grating alters our perception of the world in selective ways: Contrast thresholds for gratings of similar spatial frequency are elevated and the perceived spatial frequencies of gratings of nearby ( $\approx .5$  octave away) spatial frequencies are biased away from the spatial frequency of the adapting grating (the perceived spatial frequency shift). Although it is natural to assume that these two phenomenon arise from the same fundamental adaptational process, some evidence in the literature challenges that assumption.

Klein et al. (1974) showed that there are some fundamental differences between the perceived spatial frequency shift (PSFS) and the contrast-threshold elevation (CTE) effect. Specifically, they found that the PSFS has the same properties whether it results from prior exposure to an adapting grating or from simultaneous exposure to a surrounding grating, whereas the contrast-threshold elevation effect occurs only after exposure to a spatially superimposed adapting grating. A surrounding grating has no effect. Klein et al. concluded from these findings that the CTE and the PSFS were fundamentally different forms of pattern adaptation, and furthermore, that there was a dissociation between detection and discrimination.

The dissociation between detection and discrimination has recently been supported by the

finding (Burbeck, 1987) that frequency discrimination is not based on retinal spatial frequencies (as measured in cycles/degree of visual angle), but is based on a higher-level representation in which information about the distances to the gratings is included to achieve estimates of the actual properties of the objects. In short, in spatial frequency discrimination, observers compare the perceived, not the retinal, spatial frequencies of the gratings. Contrast detection thresholds, on the other hand, appear to be determined solely by the retinal spatial frequencies of the gratings, independently of their perceived spatial frequencies (DePalma and Lowry, 1962).

In the present study, we investigate this dissociation in more detail by exploring further the conclusion of Klein et al. that there are two fundamentally different types of pattern adaptation. Specifically, we test the hypothesis that the effects of adaptation on perceived spatial frequency occur at a site in which the perceived spatial frequencies themselves are actually represented (e.g., at the neural representation that is the basis for spatial frequency discrimination). We know already (Blakemore et al. 1972) that the effects of pattern adaptation on contrast detection depend on the retinal spatial frequency of the adapting grating. If the PSFS that results from prior adaptation also depends on the retinal spatial frequency of the adapting grating then it is less likely that there are two fundamentally different forms of pattern adaptation. On the other hand, if the PSFS depends on the perceived spatial frequency of the adapting grating, then there clearly must be two forms of pattern adaptation. In either case, the fact that the perceived spatial frequency is affected by the presence of a surround, whereas detection thresholds are not, still points to a dissociation between detection and discrimination. The question at issue here, then, is whether there are two fundamentally different effects of prolonged adaptation to a high contrast pattern.

Throughout this manuscript, we refer to a retinal-spatial-frequency representation. This usage is convenient because the stimuli are sinewave gratings, and it conforms, approximately, to

prevailing theories. However, the conclusions apply to any direct representation of the spatial information in the (monocular) retinal image. Analogously, the perceived spatial frequency representation need not be organized on the principle of spatial frequency analysis for our conclusions to apply, but need only carry the information about the perceived spatial frequency in an immediately addressable form.

## **II. SITE OF THE PSFS**

### **A. PSFS with Test and Adapting Stimuli at Different Viewing Distances.**

In our rendition of the classical pattern adaptation experiment, the adapting and test gratings are presented at different viewing distances. When the test and adapting gratings are presented at the same viewing distance, as they ordinarily are, the relationship between the perceived spatial frequencies of the adapting and test gratings is the same as that between their retinal spatial frequencies. However, when they are presented at different viewing distances and depth information is available to the observer, that connection is broken, because when their retinal spatial frequencies match, their perceived spatial frequencies differ, and vice versa. This is the basis of the experiments described below.

One could determine whether the PSFS is a function of the retinal or perceived spatial frequencies by conducting a complete PSFS study with the test and adapting gratings at different viewing distances. However, a judicious choice of test and adapting frequencies makes the complete study unnecessary. By using an adapting/test pair in which the adapting grating has a lower retinal spatial frequency than the test grating, but a higher perceived frequency, we can distinguish between the two possibilities in a single experiment.

The rationale for the choice of stimuli can be explained most easily by reference to typical PSFS curves. Figure 1 shows the PSFS data obtained by Blakemore, Nachmias and Sutton (1970), and those obtained by Klein, Stromeyer and Ganz (1974). If the adapting frequency is

lower than the test (negative value on the abscissa), then the frequency of the test appears higher following adaptation (frequency ratio  $>1$ ); if the adapting frequency is higher than that of the test, the frequency of the test appears lower following adaptation. The peak effects occur when the adapting and test gratings differ by about 0.5 octave. By making the retinal frequency of the adapting grating lower than that of the test and its perceived frequency higher by the same amount, opposite predictions are achieved: If the PSFS is tied to the retinal spatial frequencies, then the test grating should appear to have a higher spatial frequency following adaptation; if the PSFS is tied to the perceived spatial frequencies, then the test grating should appear to have a lower spatial frequency following adaptation.

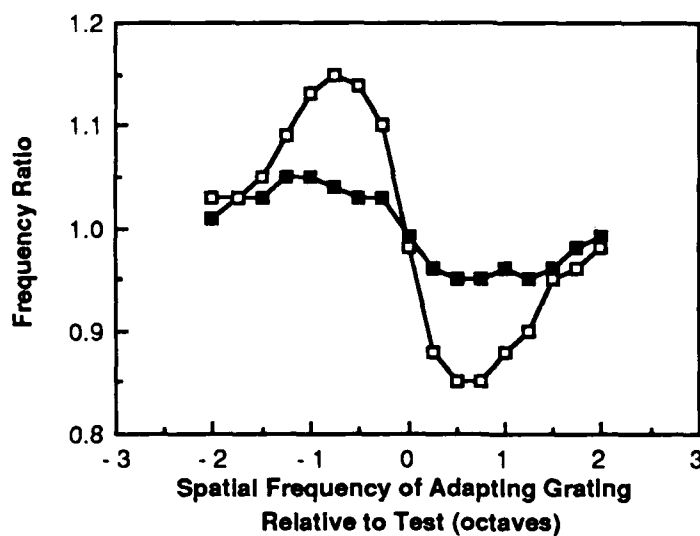


Figure 1 PSFS curves. Open squares show the data of Blakemore, Nachmias and Sutton (1970) as reported by Klein et al. (1974). Filled squares show the data of Klein et al. (1974).

### Methods

The stimuli in all of the following experiments were displayed on CRT monitors (Conrac C2400, 512x512, 60 Hz noninterlaced), with mean luminance of 78 cd/m<sup>2</sup>. The room was dimly lit (approximately 3 cd/m<sup>2</sup>), and viewing was binocular to facilitate acquisition of depth information.

A head rest was used to keep the viewing distance constant. The stimuli were all horizontal sinewave gratings. The adapting grating was presented on one monitor, the test grating on another. The two monitors were placed so that the observer perceived them as side-by-side. The observer simply shifted his gaze between them at the beginning and end of each test interval.

The adapting grating was restricted to the upper half of an 8 degree bipartite field, viewed at 1 m. The retinal spatial frequency of the adapting grating was 1.88 cycles/degree and its object spatial frequency was 1.08 cycles/cm. The adapting grating had a contrast of 80% and was flickered in counterphase at 2 Hz to prevent local adaptation. Control experiments were also conducted in which adaptation was to a uniform field. During the adapting intervals, the lower hemifield was always uniform at the mean luminance of the other hemifield. A small bar was presented in the middle of the display, which the observers were instructed to fixate. The initial adaptation interval was 1 minute and the intertrial adaptation intervals were 15 seconds.

The test gratings were also presented on an 8 degree bipartite field with a central fixation bar, but at a viewing distance of 2 m. During the test interval, two gratings were presented simultaneously, one in each hemifield. The observer's task was to report whether the upper or lower hemifield contained the grating of higher spatial frequency. No feedback was given.

The test gratings were presented for 225 msec to reduce the likelihood of the observer inadvertently making a large saccade during the test interval. The trials were timed so that the observers could saccade from the adapting field to the test field and fixate the central bar before the test stimuli were presented. The interval between presentation of the adapting and test stimuli was 1.2 sec. The contrasts of the test gratings in the two hemifields were varied randomly and independently in the range 40 to 60%, to prevent perceived contrast from being used as a cue to frequency. The mean luminance of both hemifields was constant and equal throughout the experiments. Grating phase was varied randomly and independently in the two hemifields (over the range 0 to 180 degrees). The spatial frequencies of the two test gratings differed by 2, 4, 6, 8, 10,

12 or 14 %. The average retinal spatial frequency of the two test gratings was 2.6 cycles/degree, and their average object spatial frequency was 0.76 cycles/cm. Thus, the perceived frequency of the test grating was lower than that of the adapting grating, but its retinal frequency was higher than that of the adapting grating.

### Results

Results of the adapted and unadapted conditions for two observers are shown in Figs. 2 and 3. The frequency ratios are shown in Fig 2, and the psychometric functions underlying those values are shown in Fig. 3. It can be seen that pattern adaptation raises the perceived spatial frequency of the grating seen in the (upper) adapting hemifield. This is what one would expect on the basis of the retinal spatial frequencies of the adapting and test gratings. However, it contradicts the prediction based on the perceived spatial frequencies of the gratings. Thus, the PSFS, like the CTE, must occur at a stage of processing in which the spatial properties of the retinal image itself are represented, a stage that must precede estimates of object properties.

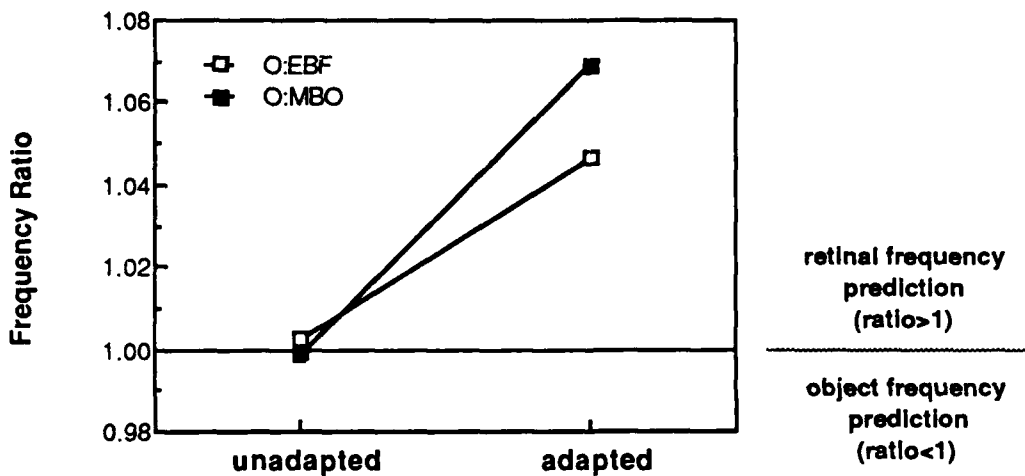


Fig. 2 Ratio of spatial frequencies of upper and lower test fields that observers perceived as matching. Data are shown for judgments made with and without prior adaptation to a high contrast grating. The effect of pattern adaptation is tied to the relationship between the retinal spatial frequencies of the test and adapting gratings, not to the

relationship between their perceived spatial frequencies. Data are shown for two observers.

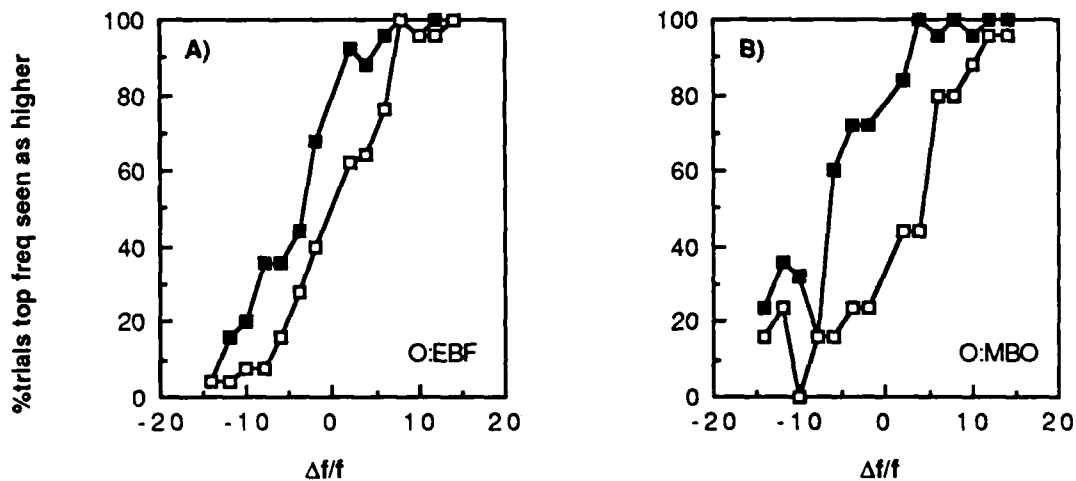


Figure 3 Psychometric functions underlying the frequency ratios shown in Fig. 2. Adapted data are shown by the filled symbols, unadapted by the open symbols.  $\Delta f/f$  is the spatial frequency in the upper test hemifield minus that in the lower hemifield, divided by the average spatial frequency. Data for two observers.

## B. CTE with Test and Adapting Stimuli at Different Viewing Distances

Before concluding that the PSFS and the CTE both occur at a stage of visual processing in which retinal spatial frequencies are represented, we replicated part of the Blakemore et al. study on the site of the CTE. Specifically, we measured the CTE with the adapting and test gratings at the same viewing distance and at different distances. If the effect is tied to the retinal spatial frequencies, as Blakemore et al. speculated, then the data obtained under the two conditions should peak at the same retinal spatial frequencies, independently of differences in the perceived spatial frequencies.

## Methods

Two experimental conditions were used in these contrast detection experiments. In the *equidistant* condition, the test and adapting gratings were both presented three meters from the observer. In the *non-equidistant* condition, the test and adapting gratings were presented at 3 meters, and one meters, respectively. The stimuli subtended 5.3 degrees at 3 m and 15.6 deg at 1 m. The retinal spatial frequency of the adapting grating was 4 cycles/degree in both the equidistant condition and the non-equidistant condition. However, the perceived spatial frequencies of the adapting gratings in the two conditions differed by approximately a factor of three, consistent with size constancy.

The adapting grating had a contrast of 80% and flickered in counterphase at 2 Hz to prevent local adaptation. The initial adaptation period was one minute and the inter-trial adaptation periods were 15 seconds.

The spatial frequency of the test grating was varied to determine the spatial frequency at which the peak adaptation effect occurred. The test grating was on for 500 msec with an abrupt onset and termination and also flickered in counterphase at 2 Hz. Detection thresholds were measured by a yes/no staircase procedure, with two interleaved staircases (Cornsweet, 1962). At least ten contrast reversals were used to estimate each threshold. In the unadapted sessions, the same procedures were used, but the adapting stimulus was a uniform field of the same mean luminance as the other stimuli. CTE ratios were calculated by dividing the contrast threshold obtained after adaptation to the grating by the contrast threshold obtained after adaptation to the uniform field.

### *Results*

Figure 4 shows the CTE ratios for the equidistant condition (open symbols) and for the non-equidistant condition (filled symbols) plotted as a function of the retinal spatial frequency of the test grating. The magnitude of the threshold-elevation is comparable to that obtained previously

(Blakemore *et al.*, 1972). The solid arrows show the retinal spatial frequency of the adapting grating. The shaded arrows show the retinal spatial frequency at which the test and adapting gratings have the same perceived spatial frequency in the non-equidistant condition.

The contrast threshold is elevated most at 4 cycles/degree regardless of the relationship between the perceived frequencies of the test and adapting gratings. Thus, it seems reasonable to conclude that both the PSFS and the CTE occur at a stage of processing in which retinal spatial frequencies are represented.

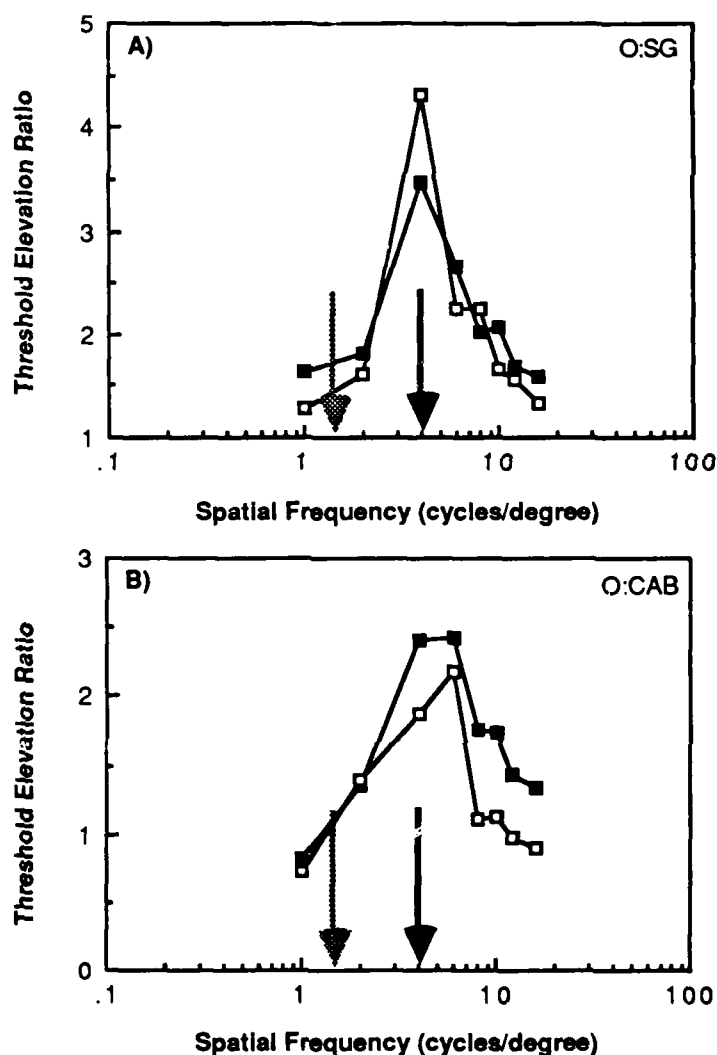


Figure 4. Threshold elevation ratios for detecting a grating at 3 meters following adaptation to a high contrast grating of 4 cycles/degree. Adapting grating at 1 meter (filled squares) or at 3 meters (open squares). The solid arrows indicate the retinal spatial frequency of the adapting grating. The shaded arrows show the spatial frequency of the test grating at which the perceived frequencies of the test and adapting gratings in the non-equidistant condition match. Data are shown for two observers.

### III. RELATIONSHIP BETWEEN PSFS AND FREQUENCY DISCRIMINATION THRESHOLDS

The PSFS also has implications for the effects of pattern adaptation on frequency discrimination thresholds. If observers make frequency discrimination judgments on the basis of perceived spatial frequency as previous research suggests (Burbeck 1987), then changing the perceived spatial frequency could result in a change in the frequency discrimination thresholds. Specifically, if the frequencies of the two gratings in a frequency-discrimination test pair straddle the adapting frequency (one higher and one lower in spatial frequency), then the test frequency that is higher will appear higher still (the PSFS), whereas the test frequency that is lower will appear lower still (also the PSFS). Thus, the perceived difference between these two frequencies should be greater following adaptation. In other words, when the test frequencies straddle the adapting frequency, the PSFS predicts that adaptation will enhance sensitivity to the frequency difference, and hence decrease the frequency discrimination threshold. But, if the test frequencies are both higher or both lower than the adapting frequency, and within the range of the PSFS effect, then their perceived difference may be smaller following adaptation resulting in higher frequency discrimination thresholds.

The exact changes in frequency discrimination thresholds that this analysis predicts are easily calculated. Before pattern adaptation, a 3% difference in stimulus frequencies results in a just-detectable difference in the perceived frequencies (i.e., 3% is the unadapted frequency discrimination threshold under our experimental conditions). After pattern adaptation, a 3% difference in the stimulus frequencies may or may not result in a discriminable difference in the perceived frequencies because the PSFS acts as a non-linear transformation between the stimulus frequencies and the perceived frequencies, expanding some frequency differences and contracting

others, as described above. To determine what the frequency discrimination thresholds should be following pattern adaptation, the effects of this non-linearity must be determined. This was done by using the PSFS transformation to calculate the difference in stimulus frequencies that would result in a 3% difference in perceived frequencies. Linear interpolation was used with the original data to complete the PSFS functions. The assumption of local linearity of the transformation makes it trivial to invert and obtain the necessary data.

The difference in input frequencies necessary to achieve a 3% difference in perceived frequencies was calculated for the full range of center frequencies. The ratios of these frequency differences to the unadapted threshold are plotted as a function of spatial frequency in Figure 5.

This figure shows predictions based on the data of Blakemore et al. (1970) and on the data of Klein et al. (1974). The original data from these two laboratories differed significantly, as shown in Fig.1, so the predictions based on them do also. The Blakemore et al. data predict a large decrease in the frequency discrimination threshold at the adapting frequency and a small increase in the threshold above and below the adapting frequency, whereas the Klein et al. data predict only a slight overall decrease in frequency discrimination thresholds, with the largest effect occurring at the adapting frequency, and a small increase at the largest ratio of adapting/test frequency shown. Another small increase would presumably also be predicted below the lowest adapt/test ratio shown, if they had data in that range.

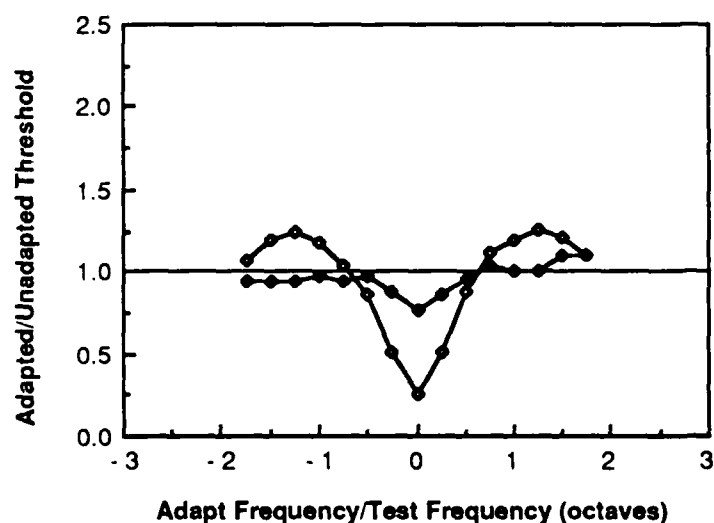


Figure 5. Effects of pattern adaptation on frequency discrimination predicted by PSFS data of Blakemore et al., open diamonds, and that based on that of Klein et al., filled diamonds.

#### IV. FREQUENCY DISCRIMINATION THRESHOLD ELEVATION

To test the predictions made above, we examined the effects of pattern adaptation on frequency discrimination thresholds. Regan and Beverley (1983) had previously conducted such a study and found that pattern adaptation elevates frequency discrimination thresholds substantially, with the largest effect occurring at 2.5 times the adapting frequency. They found little, if any, reduction in threshold at the adapting frequency. We attempted to replicate their findings, but obtained quite different results even when we adhered closely to their protocol.

##### *Methods*

Several conditions were tried; the results were the same in all of them. Data from two conditions are shown. The data shown in Figure 7 were collected under the following conditions.

*Figure 7 conditions:*

Observers viewed the stimuli monocularly at a distance of 145 cm. in an otherwise dark room. The adapting and test stimuli appeared sequentially at the same location so that no saccade was required between the adapting and test intervals. (A beam splitter and two computer-controlled shutters were used to superimpose the positions of the test and adapting stimuli, which were generated on different displays.) Adapting stimulus diameter was 9 degrees, and test stimulus diameter was 3.5 degrees (chosen to replicate Regan and Beverley's conditions). All stimuli were horizontal sinewave gratings, as in the previous experiments. The mean luminance of the adapting stimulus was 78  $\text{cd/m}^2$ , and of the test stimulus, 17  $\text{cd/m}^2$  (chosen to replicate Regan and Beverley's conditions). Adapting contrast was 80%. The test contrast was 40-60%; it was varied random from trial to trial within that range to prevent perceived contrast, which varies with spatial frequency, from being used as a cue to frequency. The phases of the test gratings were varied randomly in the range 0 to 90 degrees relative to the edge of the display.

The adapting stimuli were counterphase flickered at 2 Hz. The initial adapting duration was 5 minutes, and the inter-trial adaptation interval was 10 seconds. These adapting durations are the same as those used by Regan and Beverley. The test gratings were not flickered and were presented with the temporal envelope shown in Fig. 6. The observer's task was to indicate which grating had the higher spatial frequency. Auditory right/wrong feedback was given after each trial. In the control runs, the conditions were identical except that the adapting stimulus was uniform.

The method of constant stimuli was used, and at least 210 trials contributed to each psychometric function. The frequencies of the test gratings presented on a given trial differed by 1-7%. The average test frequency was 5.9 cycles/degree. The relationship between the test and adapting frequencies was varied by changing the adapting frequency. The adapting frequencies were: 5.9 cycles/degree (test=adapt), 2.9 cycles/degree (test=2x adapt), 2.35 cycles/degree

(test=2.5x adapt), and 1.9 cycles/degree (test=3x adapt). The data for the unadapted, the test=adapt, and the test=2.5x adapt conditions were collected in interleaved sessions, with an unadapted session being done before each adapted session. Data for the other conditions were collected later under slightly different conditions, as described below.

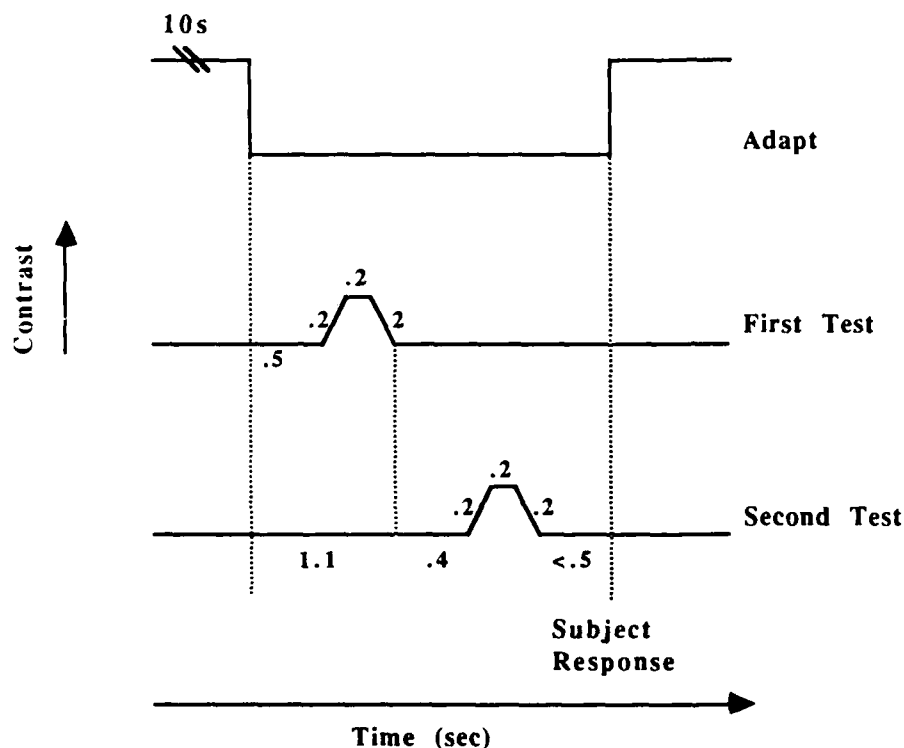


Figure 6. Temporal arrangement of adapting and test stimuli in frequency discrimination experiments.

*Figure 8 conditions:*

The data in Figure 8 were collected under conditions that are similar to those used for the data in Figure 7, with some slight modifications that were made to replicate Regan and Beverley's conditions more exactly. The contrast of the adapting grating was increased to 100% and its temporal frequency was reduced to 1.5 Hz. All other conditions remained the same. Two adapting frequencies were tested under these conditions: test = 2x adapt, and test = 3x adapt.

### *Results*

Typical pre- and post-adaptation psychometric functions for frequency discrimination obtained under our initial conditions are shown in Fig. 7. There is no evidence of elevation in any of the frequency discrimination thresholds. If anything, the frequency discrimination threshold is lower following adaptation, i.e., the psychometric function is higher. Shown in Fig. 8 are data obtained with the modifications described above, which made our conditions mimic Regan and Beverley's as closely as we could achieve. Collectively, these data show that adaptation does not elevate frequency discrimination thresholds at frequencies 2-3 times the test frequency for this naive observer. Two other observers were also tested in the test = 2.5x adapt condition, and no threshold-elevation effects were found.

To ensure that our adapting conditions did induce pattern adaptation, we measured contrast thresholds at the adapting frequency with and without pattern adaptation, using the same observer and the same adapting conditions that were used for the data shown in Fig. 8. Threshold was measured using a yes/no procedure with two interleaved staircases. Under these conditions, this observer's adapted contrast threshold was 4.4 times his unadapted threshold. Thus these conditions were effective in creating the standard pattern adaptation effect.

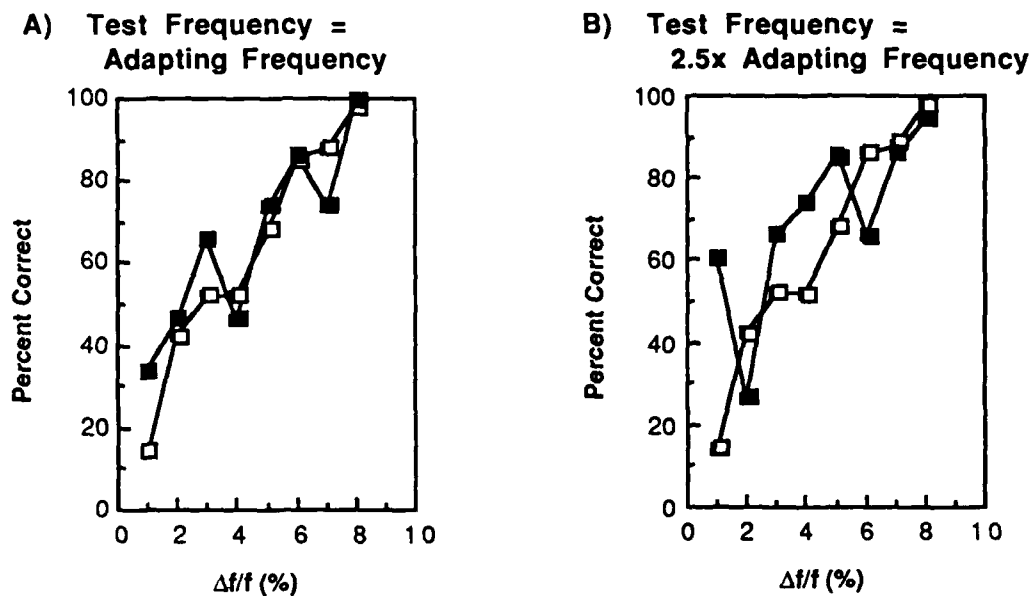


Figure 7. Psychometric functions for frequency discrimination at 5.9 cycles/degree, measured after adaptation to a uniform field (open squares) and after adaptation to a flickering grating (filled squares). The data have been corrected for guessing by the formula: (Original Percent Correct - 50) x 2. Observer: JDC A) Adapting frequency, 5.9 cycles/degree. B) Adapting frequency, 2.35 cycles/degree.

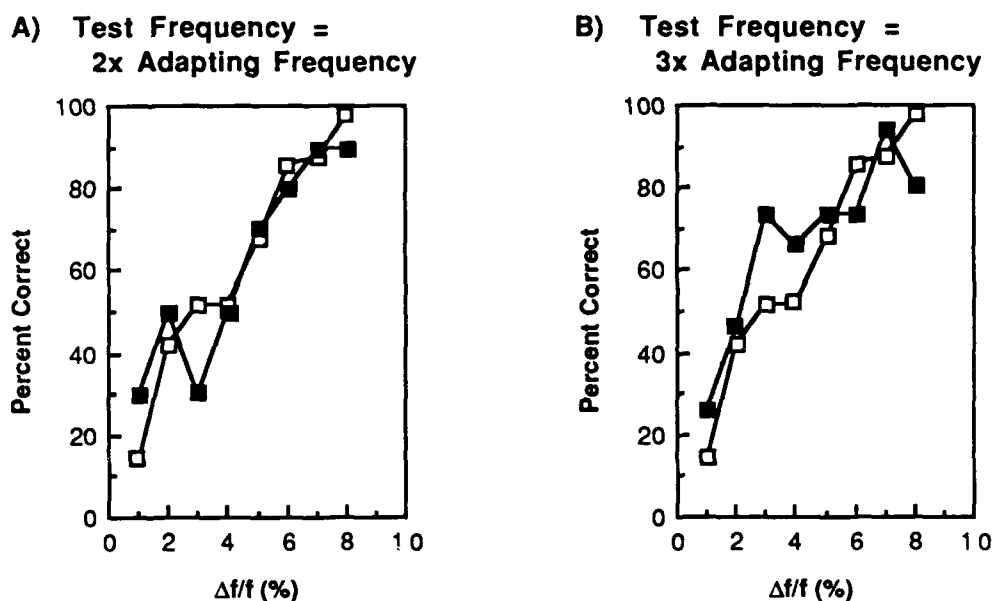


Figure 8. Same as Figure 6 except that details of adaptation and test presentation differed slightly. See text.

Observer: JDC A) Adapting frequency, 2.9 cycles/degree. B) Adapting frequency 1.9 cycles/degree.

The purpose of this experiment was to compare the effects of pattern adaptation on frequency discrimination with those predicted by the PSFS, to see if a single coherent picture emerged. Toward that end, Fig. 9(a) compares the results of our frequency discrimination experiments with the predictions made in Section III. Our PSFS results are quantitatively similar to those of Klein et al., so comparison with the prediction based on their data is most appropriate, and it can be seen that our results are in fair agreement with that prediction. However, our data are not consistent with the predictions based on the data of Blakemore et al., who obtained a much larger PSFS.

Figure 9B shows a comparison of Regan and Beverley's frequency discrimination results with both predictions. Their large threshold elevations are not consistent with either; they are not predicted even by the large PSFS found by Blakemore et al.

The PSFS reported by Klein et al. (1974), the PSFS that we find, and the frequency discrimination threshold elevation effect that we find, are all mutually consistent. However, the

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PSFS data of Blakemore et al. (1972) and the frequency discrimination threshold elevations of Regan and Beverley (1983) are not consistent with these findings or with each other, suggesting some subtle yet important differences in experimental design.

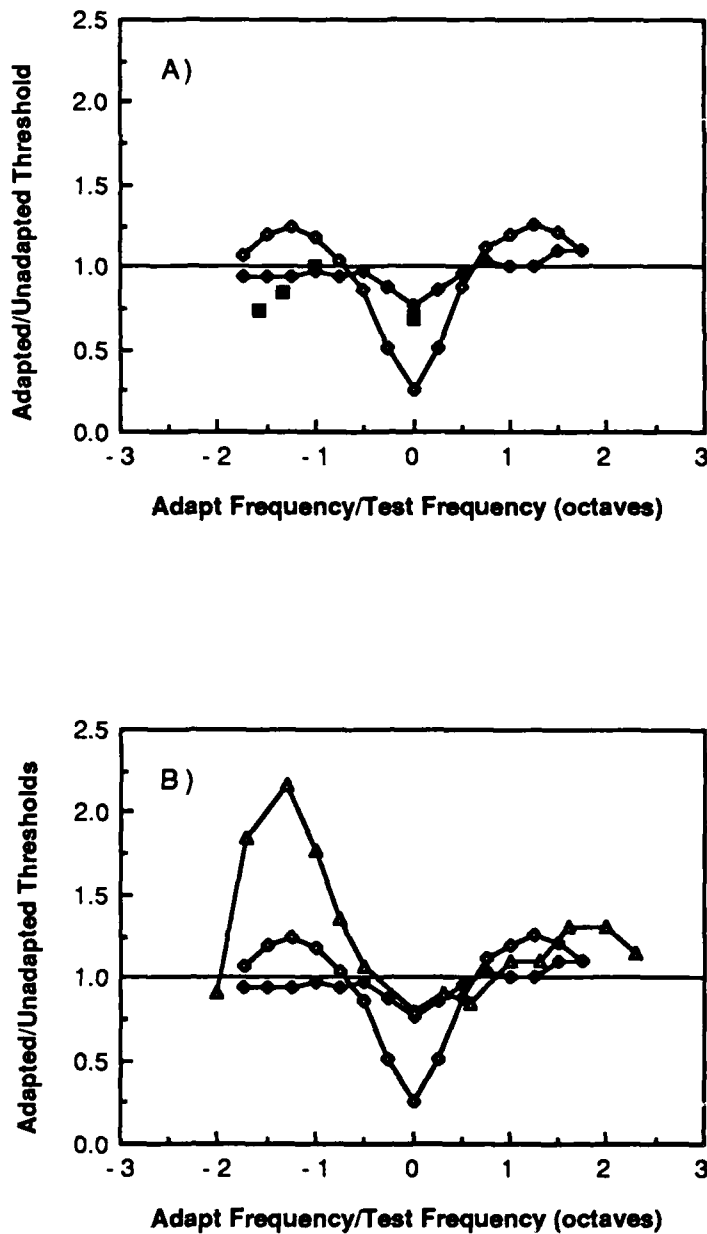


Figure 9. Comparison of experimental results on the effects of pattern adaptation on frequency discrimination thresholds with the results predicted by the perceived spatial frequency shift. The predictions based on the PSFS data of Klein et al. are shown by filled diamonds, and those based on that of Blakemore et al. are shown by open diamonds. A) Data from my lab, reported above, are shown by solid squares. B) Data from Regan and Beverley (1983, their Fig. 1) are shown by open triangles.

#### IV. SUMMARY AND DISCUSSION

We have found that the PSFS, like the CTE, depends on the relationship between the retinal spatial frequencies of the test and adapting gratings and not on their perceived spatial frequencies. Thus, pattern adaptation appears to be a fairly distal phenomenon, affecting responses at a stage of visual processing that precedes conscious perception.

We have also found that pattern adaptation affects frequency discrimination thresholds in a way that is directly predicted by the PSFS. Despite the Klein et al. (1972) finding that the PSFS produced by prior adaptation and by a surround are similar, it still seems plausible to hypothesize that (prior) pattern adaptation is a single phenomenon that affects the perceived frequency (and hence the frequency discrimination thresholds) and the contrast thresholds of subsequently viewed gratings. The effect of a surrounding grating on perceived spatial frequency may not be a form of pattern adaptation at all. Instead the surround may serve as a reference scale for the judgment of perceived frequency. In any case, the fact that a surrounding grating affects the perceived spatial frequency but not the contrast threshold of a test grating remains as evidence for the dissociation of detection and discrimination.

What does our data on the effect of pattern adaptation on frequency discrimination thresholds imply about the underlying mechanisms? The CTE and the PSFS can both be readily explained by the theory that pattern adaptation reduces the sensitivity of those channels that respond most strongly to the adapting frequency. How might this decrease in sensitivity account for enhanced discriminability at the adapting frequency? It has been suggested (Regan and Beverley, 1983; Morgan and Regan, 1987) that with high contrast stimuli, the frequency discrimination threshold at a given center frequency depends primarily on channels that respond only relatively weakly to the test frequency. The critical channels are those for which the sensitivity function is changing most rapidly with spatial frequency at the test frequencies. This means that the frequency

discrimination threshold depends on channels that are tuned to spatial frequencies somewhat above and somewhat below the test frequency. One might suppose from this that adaptation of those higher or lower channels would have the largest effect on discrimination thresholds. However, if adaptation has the effect of lowering the sensitivity of the adapted channel but not altering the shape of its sensitivity function, then there might be no change in the discrimination threshold because the rate of change of response with change in spatial frequency is unaffected. This would account for the negligible effects of pattern adaptation on frequency discrimination thresholds at frequencies above and below the adapting frequency - as we found - while still being consistent with the plausible opponent mechanism model proposed by Regan.

Another way of thinking about the effect of pattern adaptation in this context is as follows: We know that adaptation reduces the signal from the adapted channel, and when the test frequency equals the adapting frequency this means that the signal from the test channel is reduced. Weakening the signal from the primary test channel in turn provides a quieter environment for the channels that carry stronger discrimination information (that is, those that peak at somewhat higher or lower spatial frequencies). This quietening of the adapted channel would have the effect of lowering discrimination thresholds most at the adapting frequency, which is what we find, and what the PSFS predicts.

## V. ACKNOWLEDGMENTS

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